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PARTICULATE SIZING TECHNIQUES FOR CONTROL DEVICE EVALUATION

W. B. Smith, et al

Southern Research Institute

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The report describes results of laboratory and field work related to inertial particulate size classifiers (impactors and cyclones). The impactor work deals largely with non-ideal behavior of impactors and problems encountered in field testing. Preparation and handling procedures for using glass fiber impaction substrates are discussed, together with problems resulting from SO2 reactions with certain types of glass fiber filter media. The results of a brief series of tests of electrostatic effects in impactor sampling are described: they indicate that these effects can be substantial under some circumstances. Design and calibration data are given for two series cyclone size devices: one designed to operate at a flowrate of 140 liters/minute (5 cfm); and the other, at 28 liters/minute (1 cfm). Each provides three size fractionation points in the 0.5 to 10 μm size interval. The cyclone systems permit collection of larger quantities of size fractionated particulates and are somewhat easier to use than are impactors.

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This report describes the results of laboratory and field work related to inertial particulate size classifiers (impactors and cyclones). The impactor work deals largely with non-ideal behavior of impactors and problems encountered in field testing. Preparation and handling procedures for using glass fiber impaction substrates are discussed together with problems resulting from SO_2 reactions with certain types of glass fiber filter media. The results of a brief series of tests of electrostatic effects in impactor sampling are described which indicate that these effects can be substantial under some circumstances. Design and calibration data are given for two series cyclone size devices; one designed to operate at a flowrate of 140 lpm (5 cfm) and the second designed to operate at 28 lpm (1 cfm). Each provides three size fractionation points in the 0.5 to 10 μm size interval. The cyclone systems permit collection of larger quantities of size fractionated particulates and are somewhat easier to use than are impactors.

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SECTION I

INTRODUCTION AND SUMMARY

The scope of work for this contract includes investigations related to various techniques for the evaluation of pollution control devices. This report deals exclusively with inertial sizing techniques, cyclones and cascade impactors.

The impactor work done during this reporting period has to do largely with nonideal behavior and sampling problems which are encountered in field testing. Tests were run to determine the optimum jet velocities for good deposition. Laboratory tests with hard, dry, aerosols indicate that approximately 10 m/sec is the practical upper limit for jet velocities if reentrainment is to be avoided. Glass fiber substrate weight losses due to handling, preparation, and sampling were studied and it was determined that those losses are less than 0.2 mg per stage if the procedures described in the test report are used. Anomalous glass fiber substrate weight gains constitute a severe problem which can completely ruin impactor tests. It was discovered that most of those gains are due to sulfate uptake on the substrates. Several materials were tested, and preconditioning was tried to solve this problem. Teflon, Whatman GF/A and GF/D, and Reeve Angel 934 AH are glass fiber materials which showed little weight gains. Preconditioning the normal Gelman type A substrates for several hours in flue gas also led to low weight gains. A short study of electrostatic effects in impactor sampling was done. The results were not conclusive, but indicate that there are substantial interferences with bare collection plates but very little with glass fiber substrates.

Several small cyclones were evaluated during this period and the results are included in this report. Three cyclones were arranged in series and used to measure particle size distributions and to collect size segregated samples for analysis. This system is simple and reliable to operate and should be very useful in accomplishing the design functions.

Section II and Appendices A and B describe the work related to impactors while Section III and Appendix C give results for the cyclone experiments.

SECTION II

STUDIES RELATED TO THE OPERATION OF CASCADE IMPACTORS

The studies reported in this section are related to an assortment of potential problems which can occur when stack sampling with cascade impactors. Many of these problems were noted during our own field test program, some were reported by other testing groups, and some are operational problems which have been suspected but never systematically investigated. The experiments and results discussed in this section are not all complete, and in fact some serve only to illustrate the degree and nature of the problems, rather than to suggest solutions. A detailed description of our sampling systems and discussions of other research related to impactors were given in an earlier report on this contract.[1]

A. COLLECTION SUBSTRATE MATERIALS

Most impactors have collection stages which are too heavy to obtain accurate measurements of the mass of the particles collected in each size fraction. Weighing accuracy can be improved by covering the stage with a lightweight collection substrate made of aluminum foil, teflon, glass fiber filter material, or other suitable lightweight materials, depending upon the particular application. Some manufacturers now furnish lightweight inserts to be placed over the collection stages. With such arrangements, it is possible to make accurate determinations of the masses collected on various stages without the risk of reentrainment due to overloading.

The use of greased foils or lightweight glass fiber filter mats as collection substrates tends to alleviate the problem of weighing accuracy, but problems due to substrate weight changes are introduced. Although normal substrate preparation includes baking and desiccation before the initial weighing, it is frequently found that weight losses can occur when sampling clean air. Tests were conducted to investigate this phenomenon in detail. It was found that with careful handling, weight losses for glass fiber substrates can be kept below 0.2 mg. This loss is attributed to loss of fibers which stick to seals within the impactor and to "super-drying" when sampling hot, dry, air. Weight losses of 0.2 mg are small compared to normal stage catches when sampling particulate, and thus are within a tolerable range for sampling errors. The results of these experiments are given in detail in Appendix A.

When clean, hot, air is sampled with greased substrates, more severe weight losses occur. Some of the weight lost on upper impactor stages reappears as weight gained on the backup filters. This is interpreted as an indication that grease flows or is blown off the collection surface. Typical results are shown in Table I from tests of two commonly used greases which were prebaked and weighed before sampling filtered flue gas to investigate weight losses. The changes shown in this table are about as large as typical particulate catches and thus constitute serious interferences. We do not use greased foils often in our tests and therefore have not studied this effect extensively. The limited results shown in Table I indicate that a potentially serious problem does exist and that further investigations are warranted.

Substrate weight gains have been a source of very large errors when sampling industrial flue gases. Extensive studies were performed to determine the magnitude of weight gains, their cause, and to recommend solutions. These tests were initiated after it was discovered that glass fiber substrates gained as much as 4-5 mg when sampling filtered gas. These weight gains, due to gas phase

TABLE I

SUBSTRATE	DOW MOLYKOTE 111 COMPOUND	DOW SILICONE HIGH VACUUM GREASE
TEMP	300°F	280°F
FLOWRATE	0.46 ACFM	0.45 ACFM
SAMPLE DURATION	60 MIN.	60 MIN.
STAGE	WEIGHT CHANGE(mg)	
1	-1.1	-4.06
2	-0.74	-1.74
3	-0.34	-3.60
4	-0.36	-3.76
5	-0.46	-1.32
6	-0.32	-1.90
7	-0.46	-0.64
Filter	+1.86	+2.68
AVERAGE LOSS PER STAGE	0.54 mg	2.43 mg
NET TOTAL LOSS	1.92	14.34 mg

FILTERS - UNPRECONDITIONED GELMAN TYPE A (OLD TYPE)
EXPECTED FILTER WEIGHT CHANGE - ≃ 0.2 mg

reactions, seem to occur at all sites tested to some degree and often are larger than normal particulate catches.

The nature and degree of these interferences are illustrated in the following paragraphs where results obtained by running Andersen Impactors with a prefilter to remove particulate (Blank Impactor Runs) are discussed. These tests were run at the outlet of a hotside ESP on a coal fired boiler (San Juan), the outlet of a hotside ESP on a cement kiln (Citadel), and at the outlet of a coldside ESP on a coal fired boiler (Bull Run).

Two series of tests were run at San Juan, one in June 1974 and the second during January 1975. In the first series of tests no anomalous weight gains were observed, while blank runs during the second tests showed large weight gains. (It was subsequently learned that Gelman Type A filter material had been changed after the first test series.) Filter samples from the second San Juan test and the Citadel tests were subjected to several types of analyses, including carbon-hydrogen and soluble sulfate determinations, weight loss at 110° and 600°C, and carbon disulfide extraction followed by gas chromatographic analysis of the extract.

Because of the small size of the filters it was impossible to run all the tests on each filter; therefore, composites of several filters were used for some evaluations. Unfortunately, differences in individual filters could not be detected in these samples.

From the limited data on the Citadel samples there is reason to suspect the presence of an organic compound on one of the filters and soluble sulfate on another. Considerably more data would be required, however, before any firm conclusions could be drawn regarding the Citadel tests.

Preliminary data from the San Juan filters showed that soluble sulfate levels were significantly higher than obtained from unused filters from the same batch. Soluble sulfate determinations were then made on all of the filters from the two sets showing weight gains. The data in Table II clearly indicate that sulfate is responsible for the majority of the observed weight gain of each filter.

The formation of sulfate is presumed to be due to reaction of SO_2 on basic sites of the filters. Although no filters from the blank run of the initial San Juan test were available, unused filters from the same original batch were considerably less basic than unused filters from the second San Juan test and, therefore, less likely to cause sulfate formation.

Figure 1 shows in graphical form the results from San Juan Steam Plant presented in the previous table as well as data from tests at Bull Run Steam Plant. While the type of filter substrate was the same the flue gas temperature was quite different (600°F at San Juan and 300°F at Bull Run). The solid line indicates a reasonable one to one correspondence. No correlation was found between the flue gas SO_2 content and blank weight gains.

Figure 2 shows the weight gains of Blank Andersen Impactor substrates versus the temperature of the flue gas. With the exception of the Pre 6/74 point, a linear relationship seems to hold. The Pre 6/74 represents data from the first San Juan Steam Plant test shown in Table II. In this case the substrate was quite neutral compared to the basic substrates in the second test.

Figure 3 shows the results of tests of several types of 47 mm filter substrate media tested at different flue gas conditions and temperatures. It is again interesting to notice that the

TABLE II

SOLUBLE SULFATE ANALYSES OF SAN JUAN FILTERS

Unused samples from batch of first San Juan test (6/74). No samples from actual blank run (where no weight gains were observed) are available.

Sample No.	pH[a]	Total mg[b] $SO_4^=$/filter	Reported wt gain, mg
11	6.6	∿0.2	-
18	6.8	∿0.2	-
1F	6.9	∿0.2	
Set 1 from second San Juan test (1/75)			
Unused, perforated, unbaked	9.4	∿0.2	-
Unused, perforated, baked	9.4	∿0.2	-
S11	7.6	4.4	4.98
S12	7.7	4.2	4.96
S13	7.4	5.1	5.58
S14	7.0	5.0	5.56
S15	7.1	5.6	6.06
S16	7.1	5.6	6.10
S17	7.0	6.0	5.94
S18	6.8	5.6	6.04
Set 2 from second San Juan test (1/75)			
Unused, perforated, baked	9.3	∿0.2	-
Unused, solid, baked	9.7	∿0.3	-
S20	6.8	7.3	8.34
S21	6.7	5.1	5.30
S22	7.1	4.6	5.22
S23	7.4	5.2	5.40
S24	7.2	4.5	4.80
S25	7.3	5.0	5.44
S26	7.2	4.6	5.24
S27	7.1	4.9	5.50
S28	7.0	4.6	4.86
S2F	8.2	5.5	6.24

---

a. pH determined after the filter sample was in contact with 10 ml of distilled water (pH 5.6) for 1 hr.

b. The total soluble sulfate was determined by a $Ba(ClO_4)_2$ titration following a water extraction of the sample.

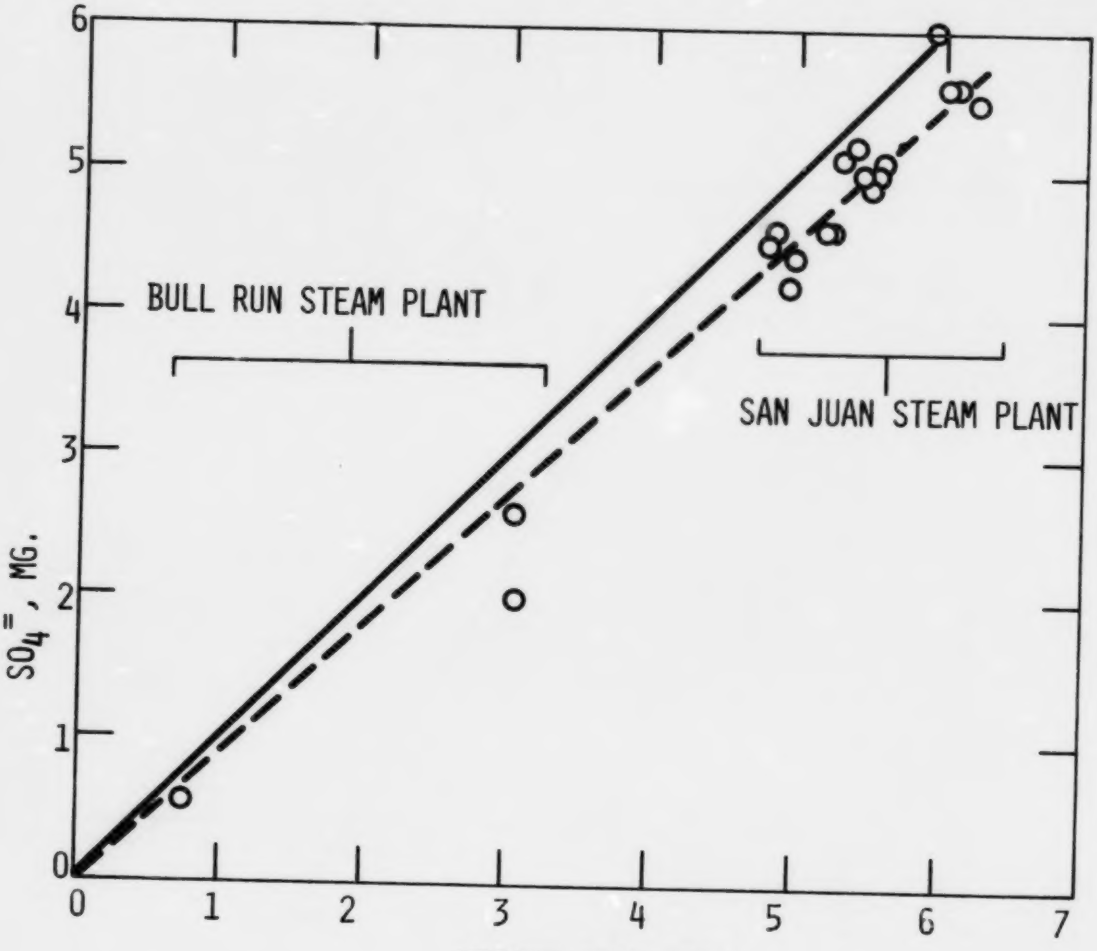

FIGURE 1. COMPARISON OF WEIGHT OF SULFATE ON BLANK ANDERSEN IMPACTOR SUBSTRATES AND OBSERVED ANOMALOUS WEIGHT INCREASES.

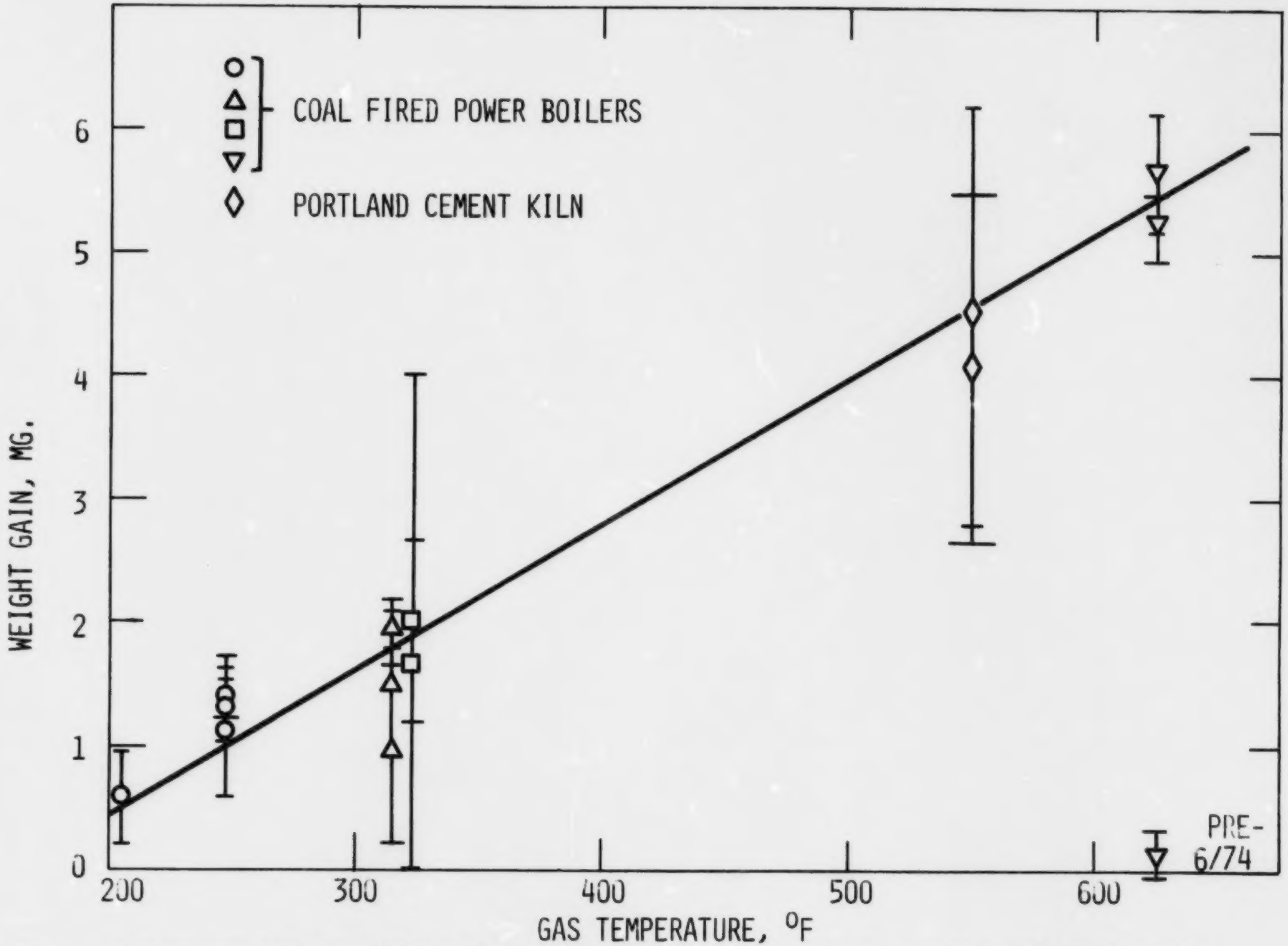

FIGURE 2. ANOMALOUS WEIGHT INCREASES OF ANDERSEN GLASS FIBER IMPACTION SUBSTRATES AT DIFFERENT FLUE GAS TEMPERATURES.

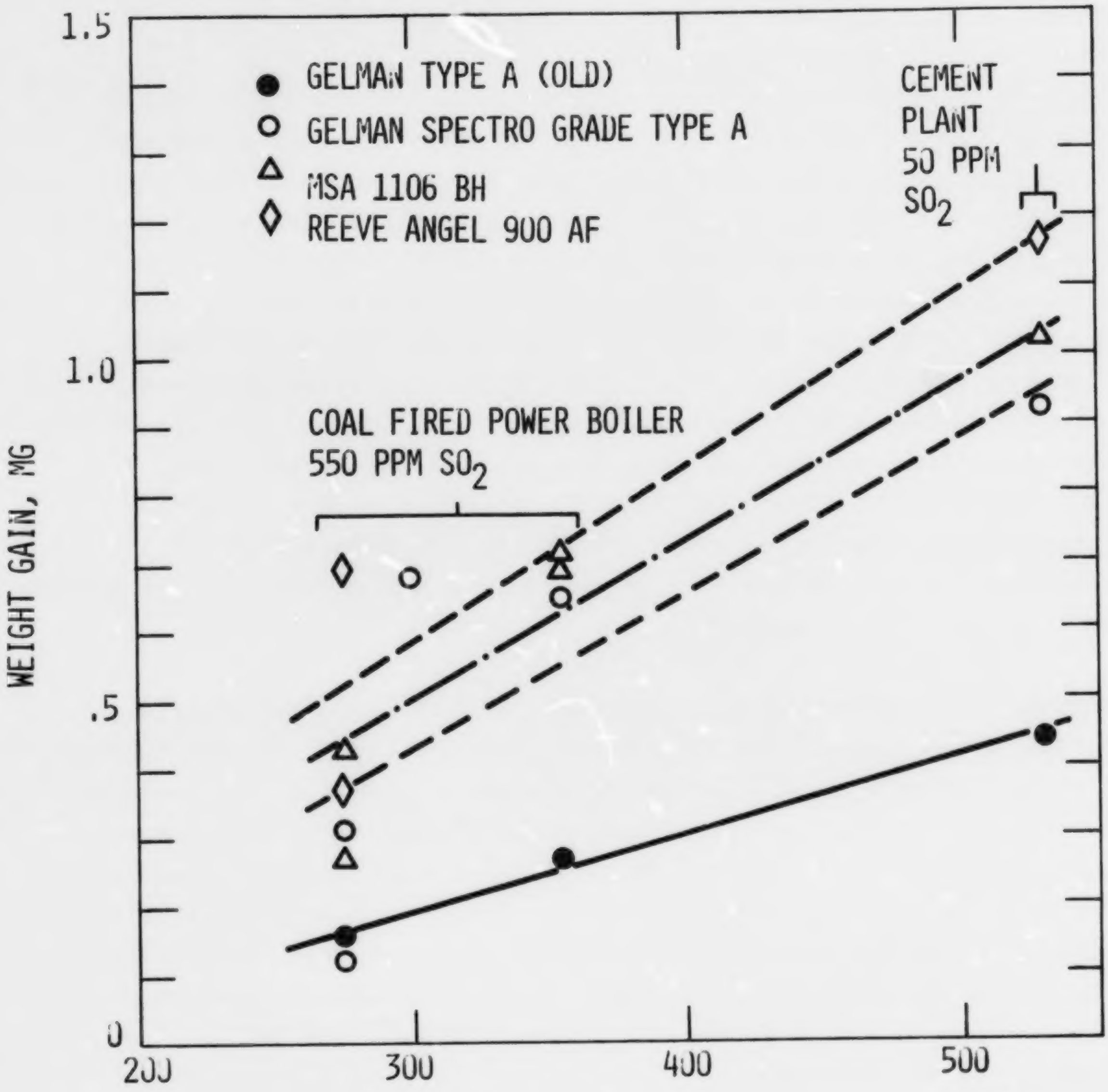

FIGURE 3. ANOMALOUS WEIGHT GAINS OF VARIOUS 47 MM DIA. GLASS FIBER FILTERS AT DIFFERENT TEMPERATURES. (60 MINUTE SAMPLES AT FLOWRATES OF 0.25 ACFM).

weight gains seem to depend more on the temperature than on the concentration of SO_2 present.

Figure 4 shows the change that preconditioning glass fiber substrates can make. Also it can be seen that even without preconditioning there appears to be a saturation limit at which the weight increases stop.

Figure 5 shows the weight gains of Andersen Impactor substrates versus exposure time for preconditioned and unconditioned substrates. The dates at the top of the figure indicate the time at which these substrates were acquired from Andersen 2000, Inc. The 6/74 Normal Substrates show an increase and leveling off with exposure time while the 6/74 Preconditioned Substrates show somewhat smaller weight gain. The "HOT" 6/74 Preconditioned Substrates would seem abnormal compared to Figure 2 but apparently the conditioning with hot flue gas reduced the weight gains for this filter set. The 1/75 Normal Substrates show a possible linear relationship, although certainly not conclusive. The Preconditioned 1/75 Substrates indicate a satisfactorily low weight gain versus exposure time.

The general procedure used to obtain samples and investigate this problem in more detail was to pump filtered flue gas through a number of stainless steel 47 mm Gelman filter holders arranged in series. The first filter served to remove the particulate, and the remaining five filters were then only exposed to the gas. Ten different types of filter media were tested at 2 industrial sites; the outlet of a hotside ESP on a cement kiln (Citadel), and the outlet of a coldside ESP on a coal fired boiler (Bull Run). The results of these tests are given in Appendix B and can be summarized as follows:

- The pH of the filters varied widely from batch to batch before testing.

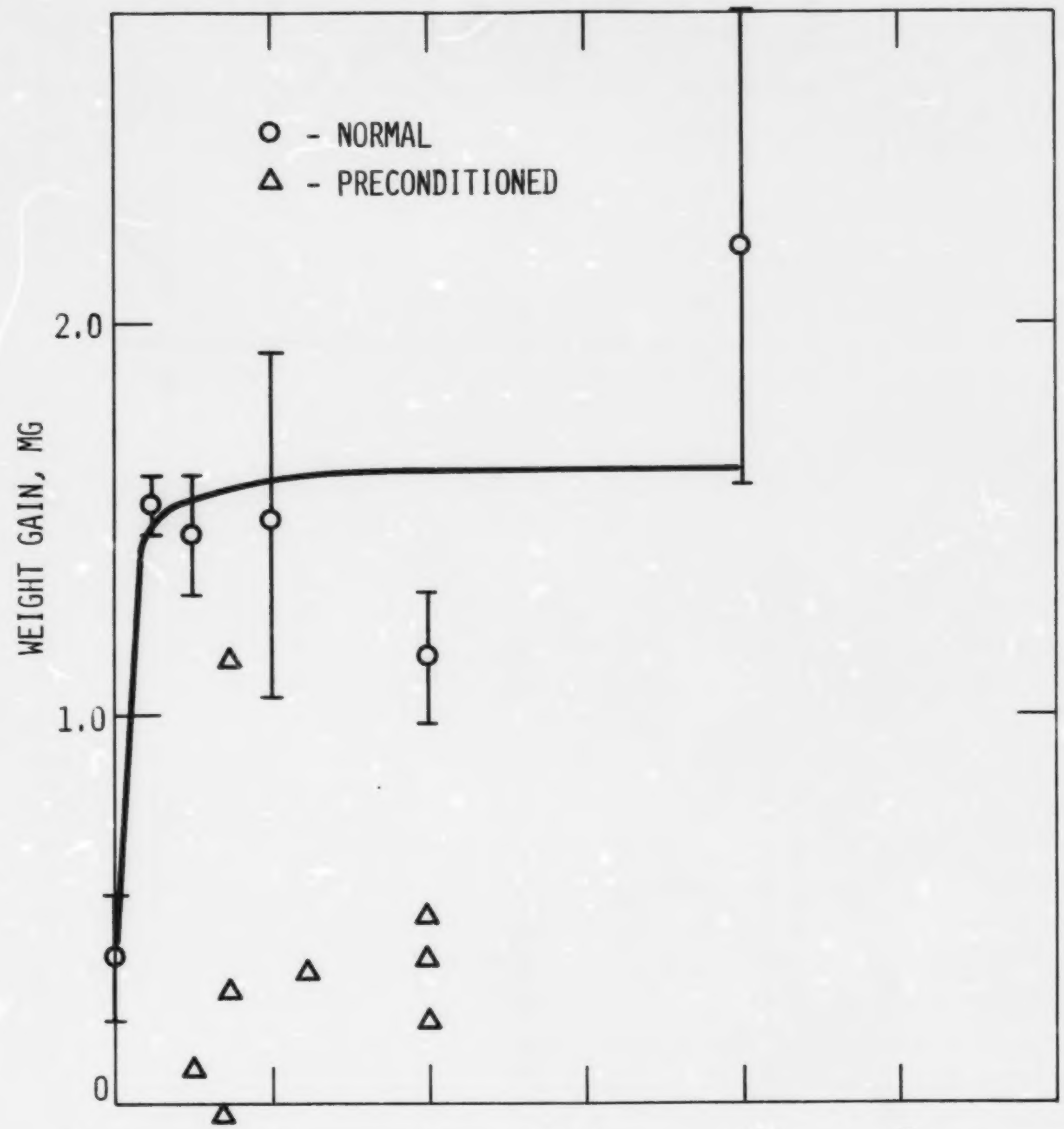

FIGURE 4. ANOMALOUS WEIGHT GAIN OF 64 MM DIAMETER REEVE ANGEL 900 AF GLASS FIBER FILTERS.

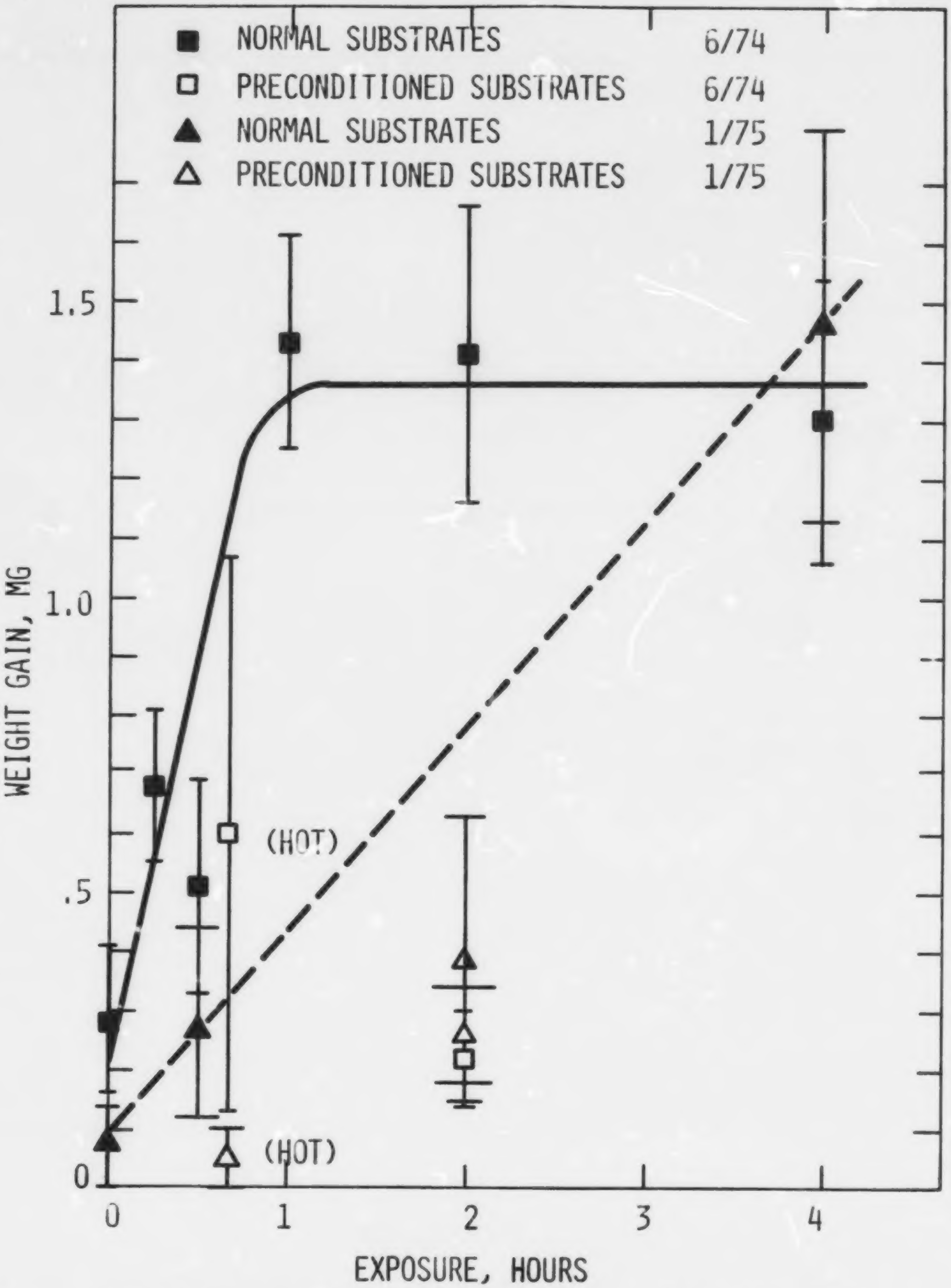

FIGURE 5. ANOMALOUS WEIGHT GAINS OF ANDERSEN IMPACTOR GLASS FIBER IMPACTION SUBSTRATES.

- There was a definite correlation between high initial pH and weight gains upon testing.

- The pH decreased during testing.

- A large fraction of the weight gain in every case was found to be the result of sulfate formation on the filter media.

- For a given temperature, the filters seem to "saturate" and not gain additional weight after a period of time (2-6 hours).

It is presumed the sulfate was formed by the reaction of sulfur dioxide with basic sites on the surface of the glass fibers. This is a phenomenon which was known to occur in ambient sampling,[2] but which had been neglected or ignored in stack sampling.

Two approaches were attempted to avoid the problems of substrate weight gains. Substrates were preconditioned by long exposure to the flue gas so that most of the basic sites were neutralized before using them, and a search was made for substrate materials which do not react with the flue gas. Preliminary results indicate that preconditioning overnight reduces the magnitude of the anomalous weight gains by approximately a factor of ten. Also, in the tests to date, Teflon, Whatman GF/D and GF/A, improved quartz, and Reeve Angel 934 AH, are filter media which show little weight change when exposed to flue gas. More tests should be made at different sites and a check made on the reproducibility of results from different batches before firm conclusions are drawn from these data. None of these materials are currently being used in cascade impactors and it is possible that their particulate retention properties could differ slightly from standard substrates. This could have the effect of altering the impactor calibrations to some extent.

B. COMPARISON OF EPA METHOD FIVE AND IMPACTOR MEASUREMENTS

If impactors performed ideally, their use should yield valid particulate mass loadings in addition to particle size distributions. On the other hand, if impactors mass loadings do not agree with the EPA Method Five it is questionable that the particle size distribution is truly representative of the flue gas aerosol.

Due to the sometimes wide disparity between grain loadings obtained with mass trains and cascade impactors a study has begun to try to isolate, explain, and to suggest possible solutions to this situation. As can be seen in Figure 6, the spread in the data is quite large, although the majority lie within a rather broad band about the perfect agreement line. The symbols on the figure can be associated with the following list of sampling sites by using the corresponding number indicated on the graph. A short explanation is given, if possible, of possible reasons for the impactor - mass train disparity.

1. Marquette, Michigan — Coal Fired Power Boiler

   January 8-20, 1973

   315°F — 7.0% Moisture

   No traversing by impactors at outlet. Stratification of dust likely. SO_2/SO_3 gas phase reaction unlikely.

2. Harrisburg, Pennsylvania — Refuse Incinerator

   May 7-11, 1973

   410°F — 12% Moisture

   Only a four point semi-traverse performed at outlet. Charred paper present in exit gas stream with sizes greater than impactor nozzle diameter.

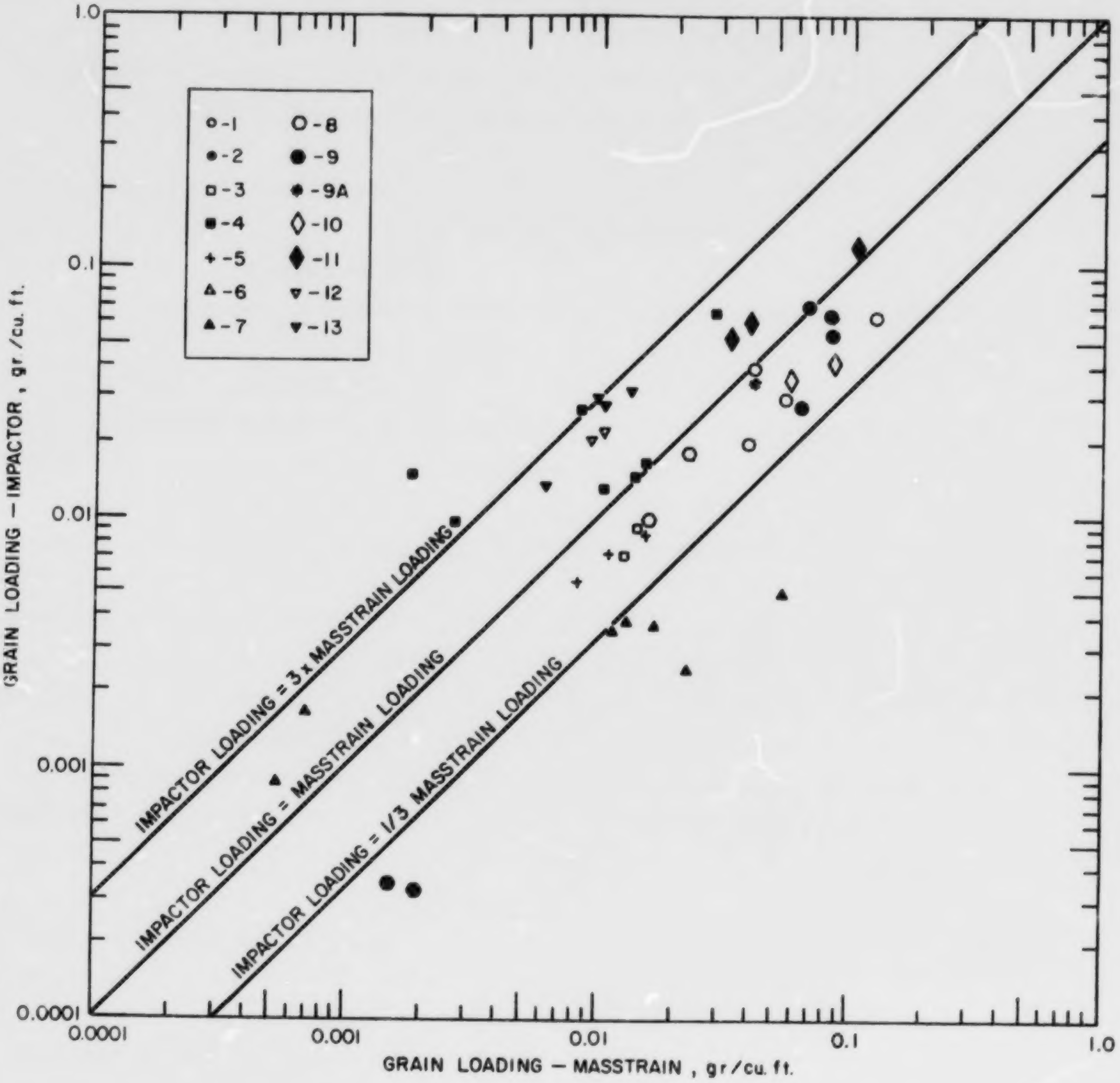

Figure 6. Grain loading by conventional (ASME, EPA) mass train versus grain loading by cascade impactor for thirteen sampling locations. All loadings refer to control device outlets except for 9A. Number references as to location are presented in the text.

3. Gorgas, Alabama Coal Fired Power Boiler

July 8-13, 1973

300°F 10% Moisture

Six point semi-traverse performed at outlet. Stratification of dust likely. SO_2/SO_3 gas phase reaction unlikely.

4. Wood River, Illinois Coal Fired Power Boiler

September 12-20, 1973

315°F 15% Moisture

Definite SO_2/SO_3 gas phase reactions occurred. No traversing performed.

5. Gillette, Wyoming Coal Fired Power Boiler

August 1 - September 7, 1973

300°F 15% Moisture

No traversing performed. SO_2/SO_3 gas phase reaction unlikely.

6. Lone Star, Texas Open Hearth Steel Furnace

December 3-14, 1973

200°F 35% Moisture

Cyclonic air flow in duct. Dead air space in center. Impactors did not traverse, but sampled two points, approximately 1/3 of duct diameter in from edge. Mass trains traversed the duct.

7. San Juan, New Mexico Coal Fired Power Boiler

April-May 3, 1974

620°F 8.0% Moisture

Mass trains may have bumped sides of duct and vertical turning vanes with nozzles pointing up. This could have caused fall off of large chunks of fly ash. Impactors use 2 and 3 point semitraverse. Stratification of coarse dust likely because of turning vanes.

8. Memphis, Tennessee Electric Arc Smelting Furnace

July 24-28, 1974

180°F 21.5% Moisture

Impactors used single point sampling. Wet stack might have caused droplets to be lost in nozzles.

9. Outlet Aluminum Reduction Pot Lines

9A. Inlet August 19-23, 1974

120°F 5.3% Moisture

At this time there is not a good reason for the disparity. Wet stack conditions allow for possiblity of water droplets being lost in nozzles. Impactor sampled 2 points in duct ~ ¼ duct diameter in from duct wall. Condensate from badly scaled duct walls was entrained in exit gas flow near duct walls.

10. Buffalo, New York Asphalt Plant

October 12-19, 1974

170°F 8.5% Moisture

Water droplets and fog/mist in the duct. Did not include material in impactor nozzles in loadings calculated from impactor data.

11. Meremac, Missouri Coal Fired Power Boiler

November 1-5, 1974

315°F 7.0% Moisture

SO_2/SO_3 gas phase reactions did occur and cause impactor substrate weight gains.

12. Pekin, Illinois Coal Fired Power Boiler

November 17-23, 1974

320°F 9.0% Moisture

SO_2/SO_3 gas phase reactions did occur and cause impactor substrate weight gains.

13. Birmingham, Alabama Cement Kiln

December 16-20, 1974

550°F 25% Moisture

Some gas phase reactions may have occurred. Some indication of condensable hydrocarbons.

Although it is not possible to clearly specify the causes of disagreement between the mass loadings measured by impactors and mass trains from the data presented above, tentative suggestions can be made as follows:

1. The dust concentration in industrial flues and stacks may vary radically with position and time. Vertical stratification has been frequently observed and sampling positions downstream from turns may introduce biased samples into either system. Unfortunately it is difficult and tedious to take a large number of isokinetic samples with impactors. Temporal variations in the dust concentration are important because the sampling time for impactors is dictated by the necessity of obtaining weighable samples without overloading any single collection surface. From a practical standpoint, this means that sampling times may vary from 1 or 2 minutes up to 10 hours. If there are large variations in concentration due to process changes, the short sampling times may not give good averages of the true mass emissions. In some cases this problem can be alleviated by using weighted averages of a large number of such samples.

2. Gas phase-substrate reactions are a definite problem for both impactors and mass trains. This is discussed in paragraph IIA and in Appendix B.

3. It is difficult to always sample isokinetically when using cascade impactors because the flowrate must remain fixed during any single test, and because the selection of practical nozzle sizes is limited. It is general practice to avoid the use of

nozzles smaller than 2 mm in diameter even if smaller nozzles are required for isokineticity. Figure 7, from our field test data, shows how particle-size distribution measurements are affected by anisokinetic sampling. In these three tests the series cyclone arrangement was adjusted to isokinetic sampling conditions, while the Brink impactor was operated with a 2.5 mm nozzle, rather than the 1.0 mm nozzle required for isokinetic sampling. It can be seen that particles larger than about 2 μm in diameter are oversampled in the Brink and that the particle-size distribution is severely distorted. In this case (which is not untypical) the Brink data are very much in error with regard to size distribution and total grain loading. This illustrates that isokinetic sampling is essential for proper impactor operation and that samples taken anisokinetically are not representative of the flue gas aerosol.

The factors listed above all contribute to the scatter and uncertainty in impactor results. There is clearly a need for a systematic approach to determine the number and type of measurements needed to obtain representative particle-size distribution measurements, and to establish substrate preparation procedures to minimize interferences due to gas phase reactions.

C. ELECTROSTATIC EFFECTS

Electrostatic forces due to charges which may exist on the flue gas particulate are a potential source of error for any sampling technique which extracts a sample through a nozzle or probe.

A short study was undertaken to determine the importance of charge neutralization on aerosols prior to sampling by a cascade impactor. Figure 8 shows a schematic of the setup of the impactor and particle counter used in this preliminary experiment. A three-stage Brink Cascade impactor was employed with a removable polonium α-source attached to the nozzle of the impactor. A flowrate of 0.1 acfm was maintained through the impactor using the pump in the

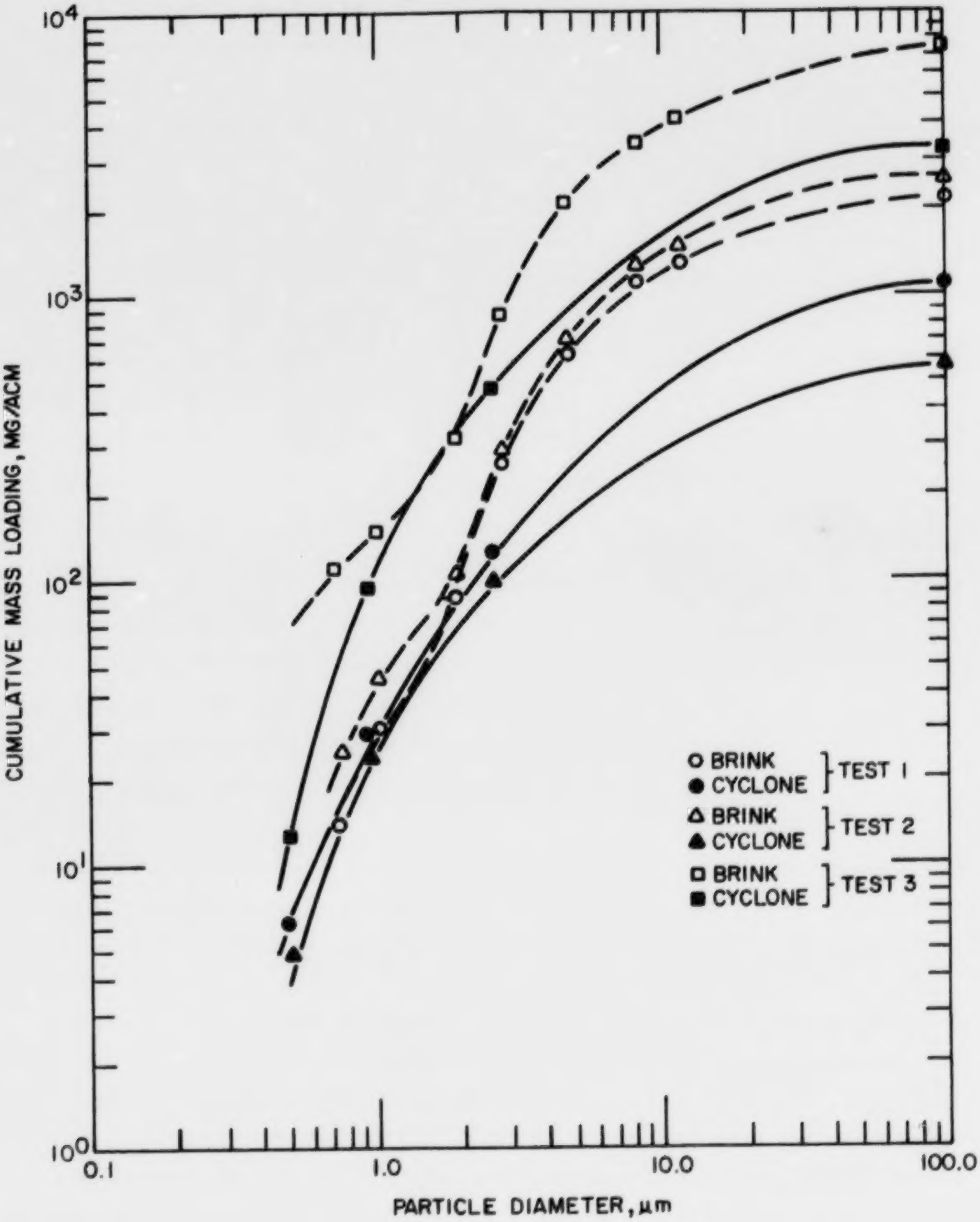

Figure 7. Comparison of results of size distribution measurements using isokinetic (cyclone) and non-isokinetic (Brink) sampling rates.

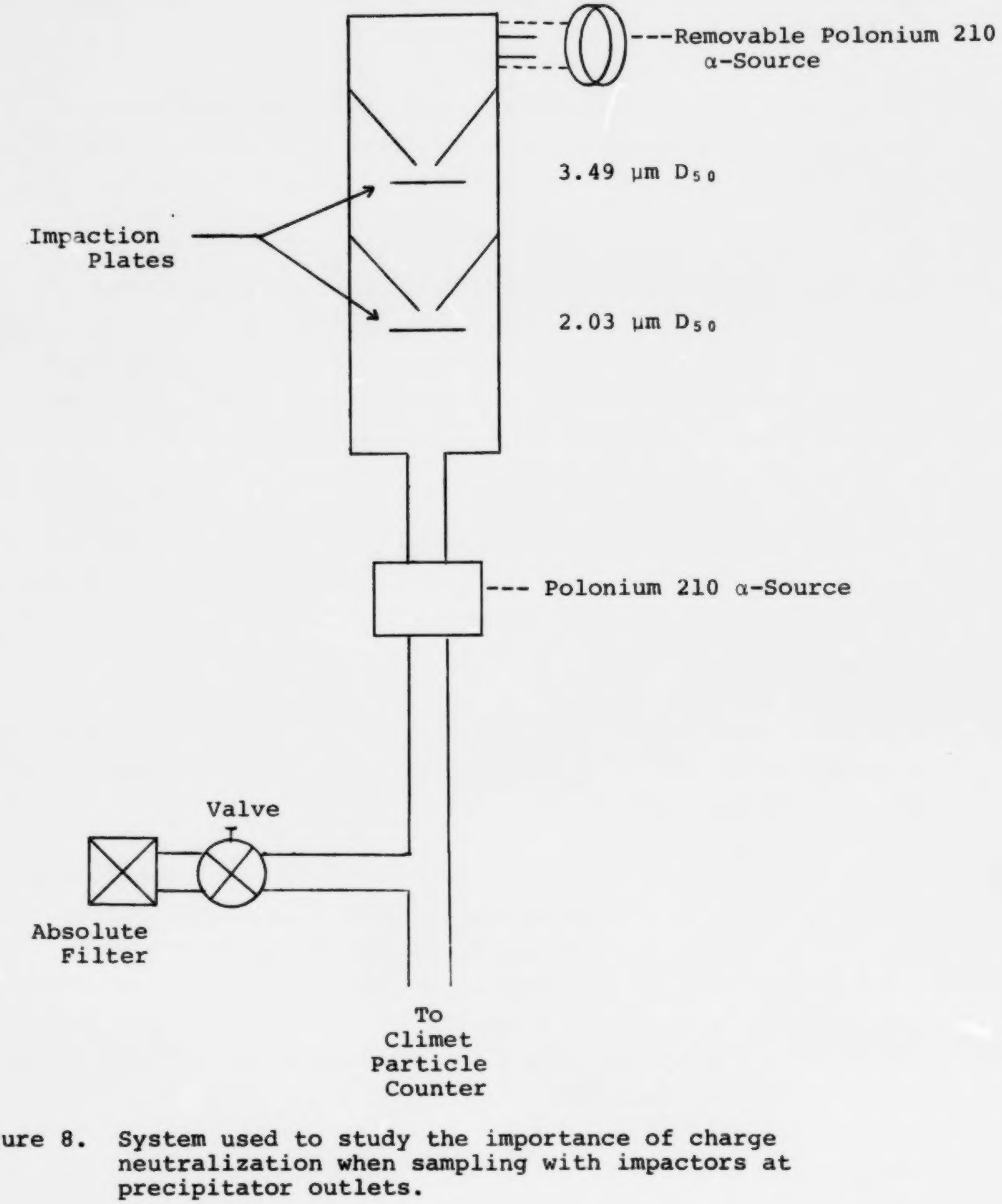
---Removable Polonium 210 α-Source
3.49 µm D50
Impaction Plates
2.03 µm D50
--- Polonium 210 α-Source
Valve
Absolute Filter
To Climet Particle Counter

Figure 8. System used to study the importance of charge neutralization when sampling with impactors at precipitator outlets.

Climet Particle Analyzer, which operates at 0.25 acfm. Make-up air to the particle counter was supplied by a controlled filtered air supply. The aerosol exiting the impactor was charge neutralized with a second polonium 210 α-source to minimize sample and instrumental losses due to electrostatic forces between the impactor and particle counter.

The aerosol was produced by a "hobby" paint sprayer producing a polydisperse DOP aerosol which was sampled by the impactor at the outlet of the model wet-wall precipitator at Southern Research Institute.

Four different configurations of the impactor were tested: (1) with glass-fiber filter substrates, (2) with bare metal plates, and (3) with no plates to study the effect of wall loss, and (4) extractive sampling with a three foot, ¼" I.D. copper probe. Each condition was tested with and without the charge neutralizer prior to the impactor nozzle.

The data from this investigation are presented in Figures 9, 10, and 11. Figure 9 indicates that there is no appreciable effect of charge neutralization when glass fiber filter substrates are used. Figure 10 indicates that there is some effect on the number of particles exiting the impactor with and without charge neutralization when bare metal plates are used. Figure 11 shows that there is essentially no wall loss within the impactor which can be attributed strictly to the electrostatic effects.

The results are plotted another way in Figure 12. The data are normalized to the concentration measured without the charge neutralizer in place. Curves are shown for the probe alone, for the impactor with glass fiber substrates (no probe), and for the impactor operated with bare metal collection plates (no probe). Losses in the probe and with bare substrates are seen to be rather large. For the tests made using glass fiber substrates there was no appreciable difference in the concentrations measured with and without the charge neutralizer.

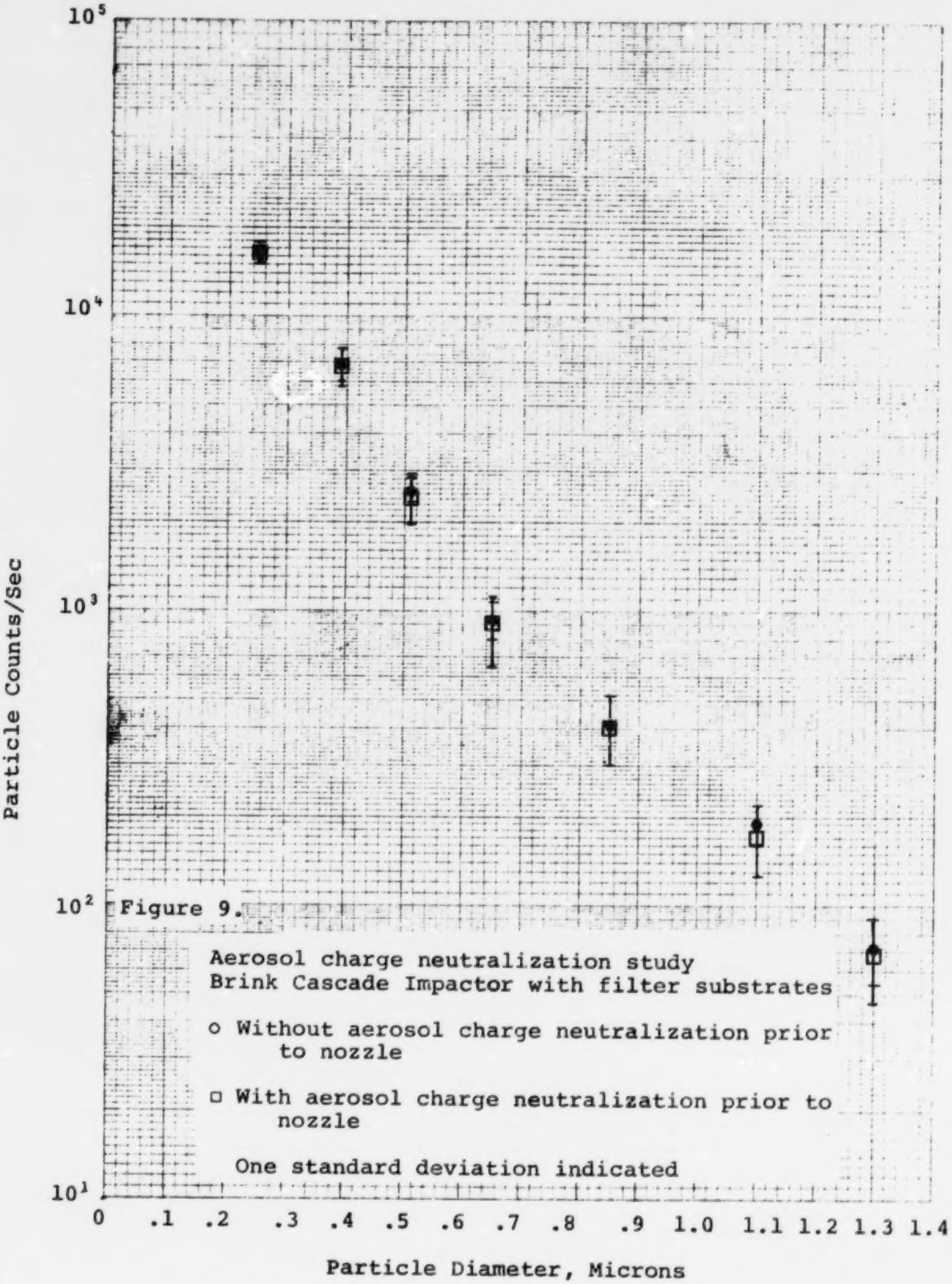

Figure 9.

Aerosol charge neutralization study
Brink Cascade Impactor with filter substrates

○ Without aerosol charge neutralization prior to nozzle

□ With aerosol charge neutralization prior to nozzle

One standard deviation indicated

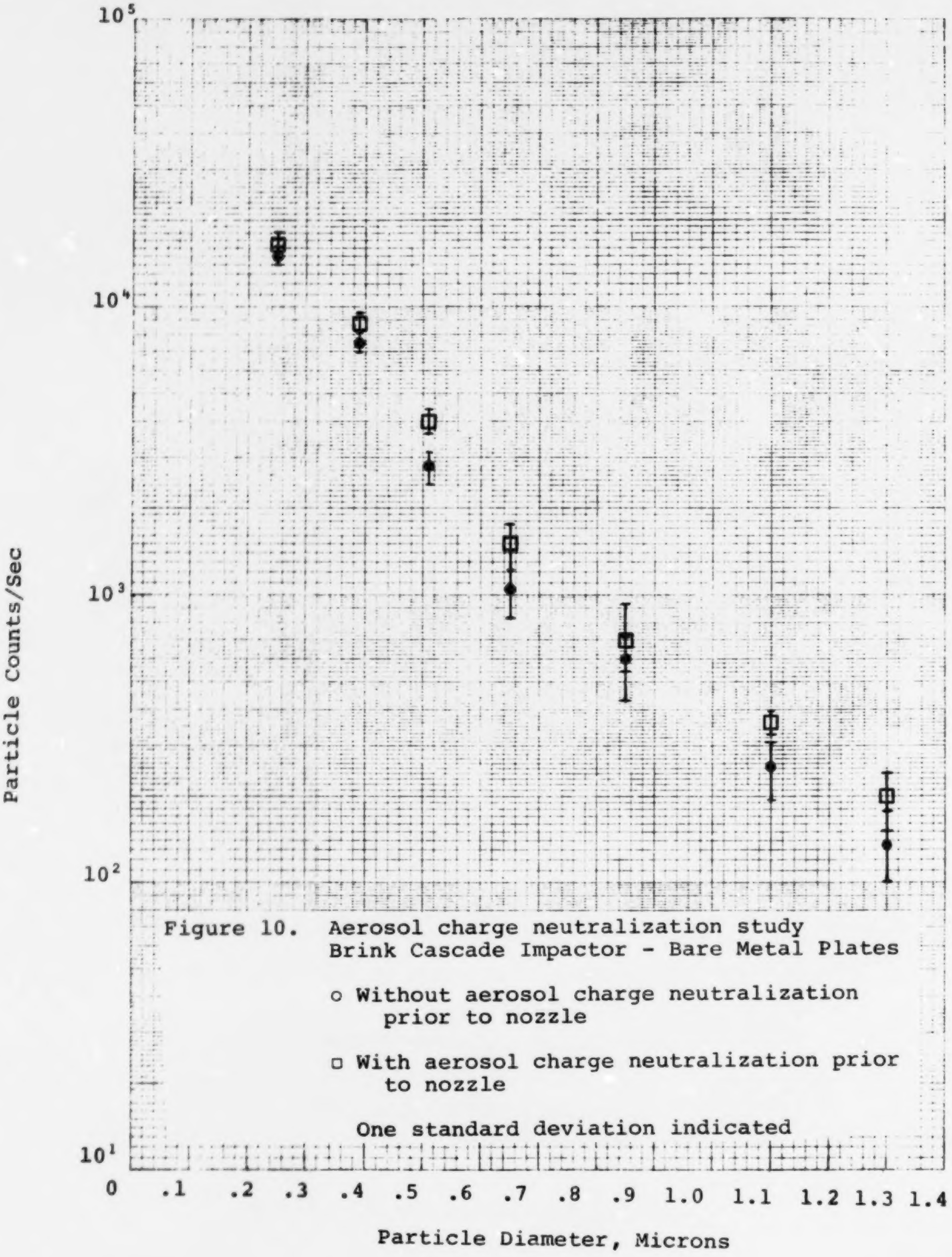

Figure 10. Aerosol charge neutralization study
Brink Cascade Impactor - Bare Metal Plates

○ Without aerosol charge neutralization prior to nozzle

□ With aerosol charge neutralization prior to nozzle

One standard deviation indicated

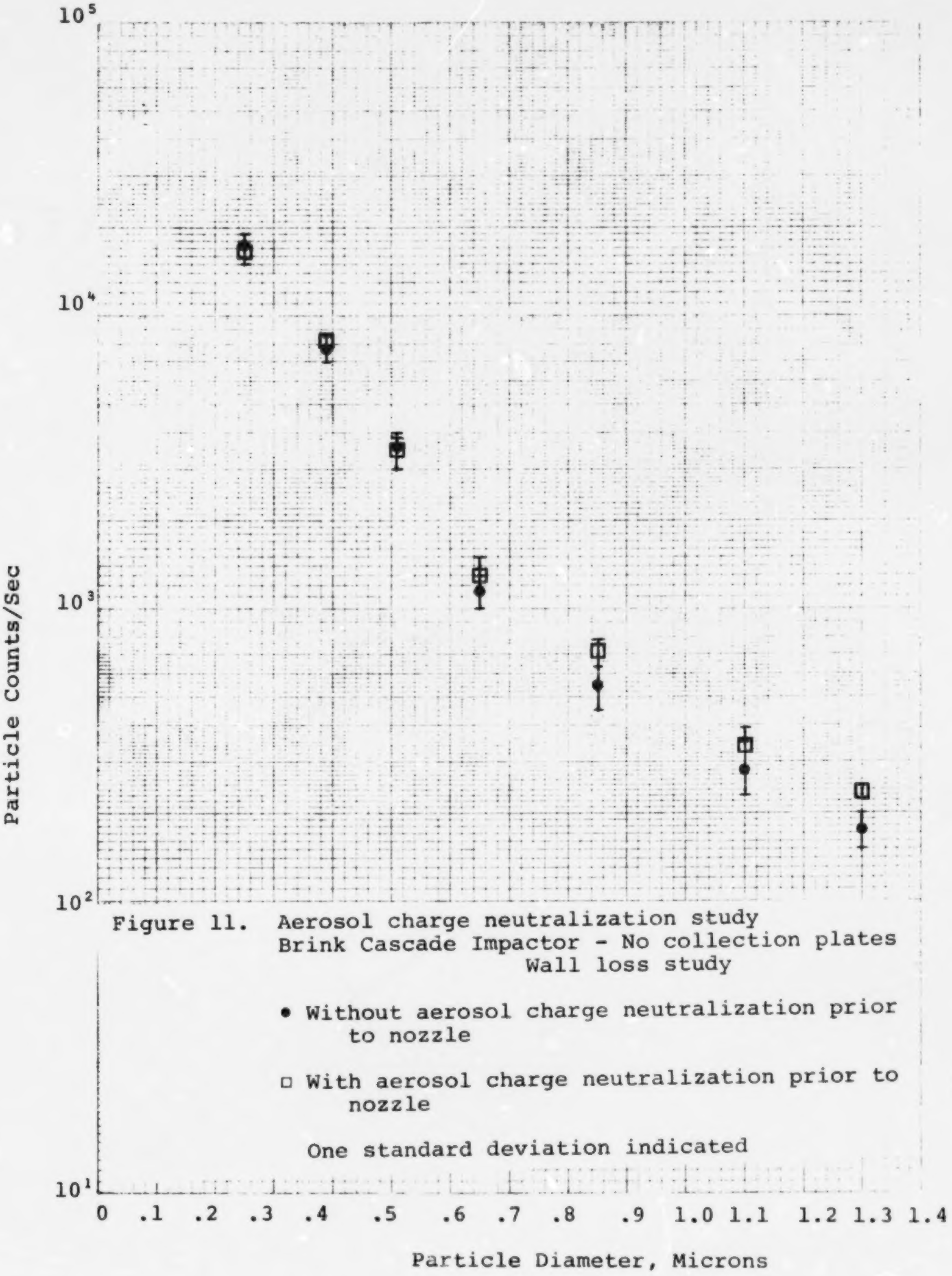

Figure 11. Aerosol charge neutralization study
Brink Cascade Impactor - No collection plates
Wall loss study

- ● Without aerosol charge neutralization prior to nozzle
- □ With aerosol charge neutralization prior to nozzle

One standard deviation indicated

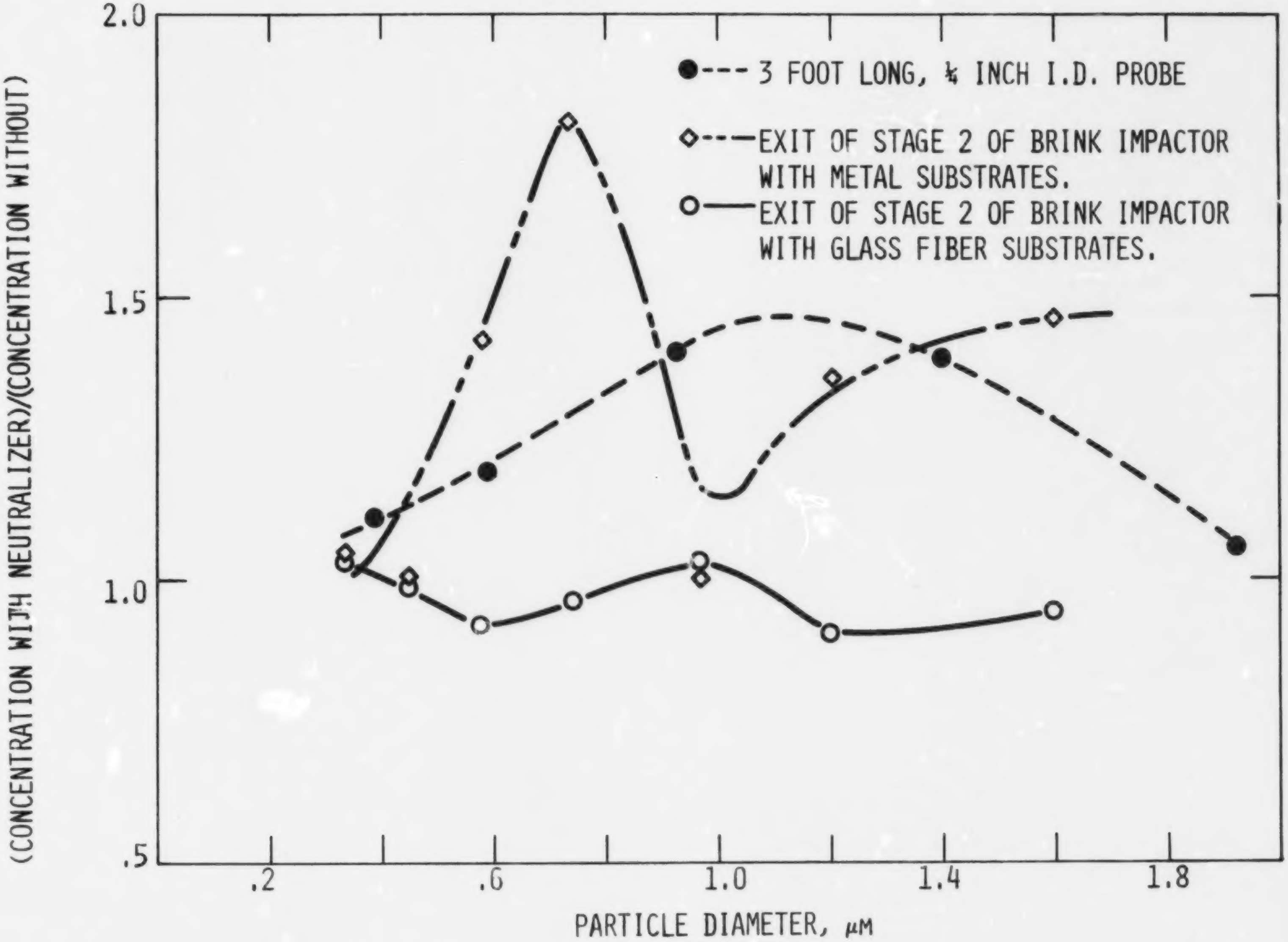

Figure 12. Electrostatic effects in probe and partial Brink Impactor. All flowrates 0.1 cfm.

These tests indicate that if cascade impactors are used without charge neutralization at precipitator outlets, serious error may occur in some cases, while accurate results could be obtained in certain situations. The study was not extensive however, and the need for a more quantitative investigation is apparent.

D. REENTRAINMENT DUE TO IMPROPER OPERATION

When impactors are operated at flowrates higher than some critical value, particle bounce can lead to incorrect sizing of non-cohesive particulates. This is especially true on the lower impactor stages where high jet velocities often cause noticeable scouring. Visual observation indicates that even with grease, erosion and scouring can occur on the lower stages if jet velocities exceed about 65 m/sec. The scouring and reentrainment problem can be minimized by reducing the flowrate of the impactor. This change in flowrate increases the cut point of each size fraction and decreases the amount of information that can be obtained in the small particle size range. However, the addition of a final stage to the impactor with the proper combination of velocity and jet diameter would make it possible to regain the information lost at the lower flowrate. This has been done on the Brink impactor by adding a "6th" stage designed and built at Southern Research Institute.

Laboratory tests were performed which indicate that flowrates of about 10 m/sec or less are optimum for the best deposition on impaction substrates. Figure 13 shows patterns of deposition obtained at jet velocities of 5 and 12 m/sec, using a hard, dry, laboratory aerosol (ammonium fluorescein). The deposition of particles at 12 m/sec shows definite evidence of scouring while the pattern formed at 5 m/sec is uniform and shows no tendency to smear out. Figure 14 shows backup filters which contain particles reentrained into the gas stream from these stages. The magnitude of the scouring effect depends greatly upon the relationship between the particle size and the stage D_{50}, being larger for particles which greatly exceed

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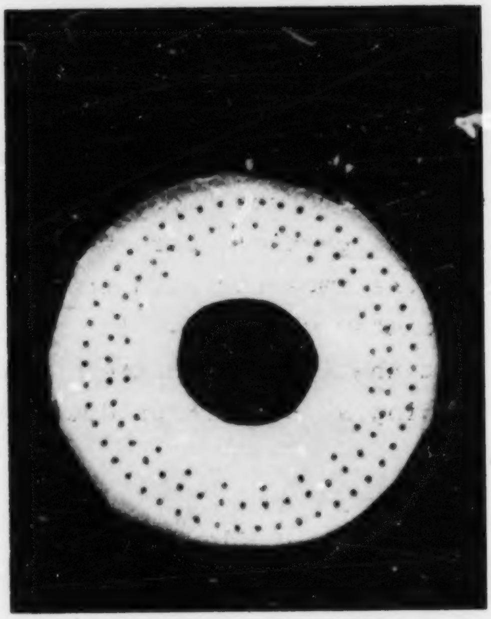

Figure 13A

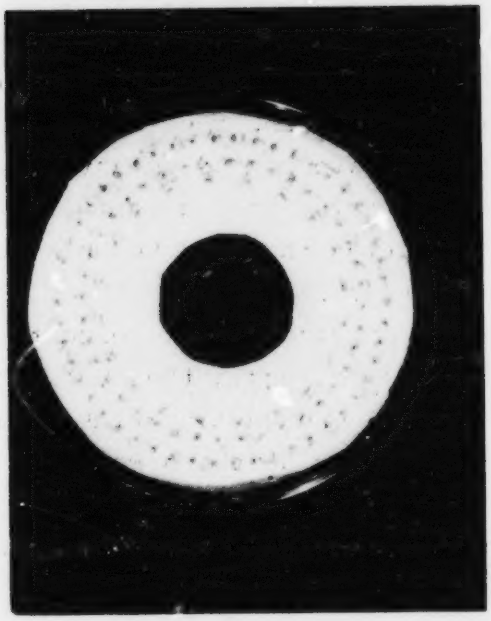

Figure 13B

Figure 13A. University of Washington (Pilat) Stage 6 0.1 cfm D_{50} = 1.0 micron. Four micron diameter monodisperse particles. The uniform particle deposition is apparent as compared to Figure 13B.

Figure 13B. University of Washington (Pilat) Stage 5 0.5 cfm D_{50} = 1.0 micron. Four micron diameter monodisperse particles. Poor particle deposition is evident with scouring around the point of impact. Figure 14 shows reentrained particles which should have remained on this substrate.

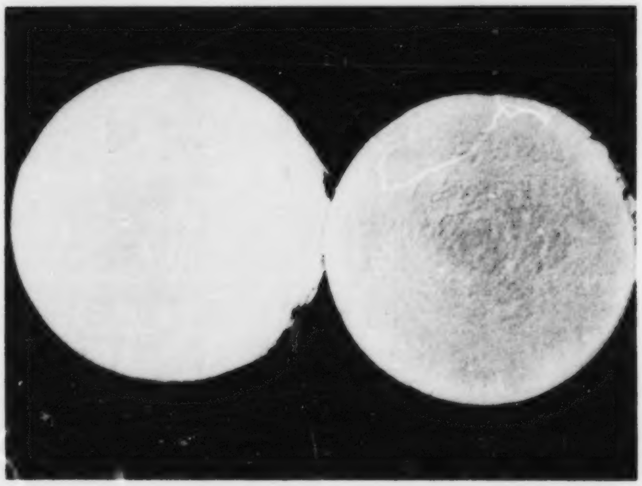

Figure 14. Left - 0.1 cfm U. of W. back-up filter
Right - 0.5 cfm U. of W. back-up filter
Filter on the right shows reentrained particles collected after passing 1.0 micron cut off stage shown in Figure 13B.

the D_{50}. In the interpretation of this data, it should be clear that the impactor was not operated in the conventional manner, and the University of Washington Impactor was chosen only for convenience in performing these tests. The object of this experiment was to demonstrate the importance of maintaining reasonable jet velocities when sampling with impactors.

SECTION III

CYCLONE SAMPLING SYSTEMS

A. GENERAL DISCUSSION

Cyclones have been used less than impactors for making particle size distribution measurements because they are bulky and give less resolution. However, in applications where larger samples are required, or where sampling times with impactors may be undesirably short, cyclones are better suited for testing than impactors. Cyclones are also frequently used as precollectors in impactor systems to remove large particles which might overload the upper stages, and to give a larger cut point than the first impaction stage.

Chang[3] developed an elaborate system of parallel cyclones which separates particles into four size fractions. This system is very large and complicated to operate, and requires extractive sampling through a probe. Although the system is impractical for stack sampling the discussion of cyclone design and calibration included in Chang's report served as a starting point for the work described in this section. Figure 15 shows a schematic of a much simpler series cyclone system which was described by Rusanov[4] and is used in the U.S.S.R. for obtaining particle size information. This device is operated instack, but because of the rather large dimensions requires an eight inch port for entry.

Two series cyclone systems were designed during this reporting period. One system was designed for approximately 5 acfm flowrate and will be operated out of stack as part of a modified Aerotherm high volume mass train. This system was not constructed at Southern Research and consequently we have no data pertaining to its calibration or performance. The second system was designed

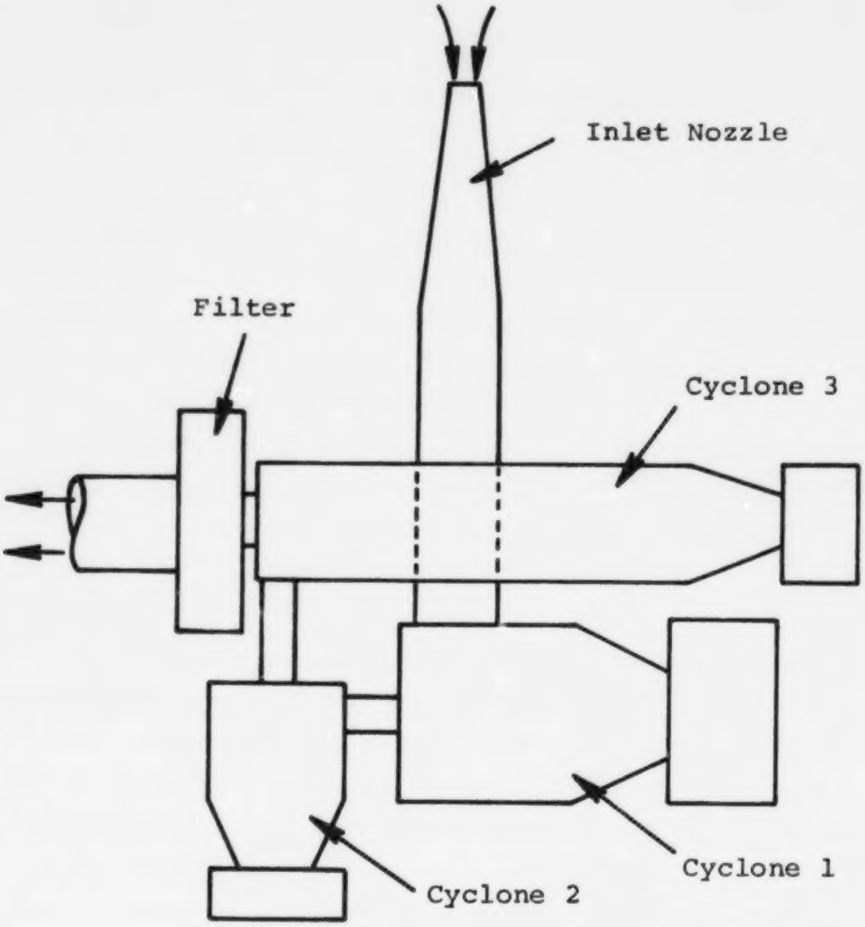

Figure 15. Series cyclone used in the U.S.S.R. for sizing flue gas aerosol particles.[4]

for 1 acfm flowrate and is compact enough to fit through a 6 inch port. Complete calibration and preliminary performance testing of this system has been done. Both of these systems have adequate resolution for many purposes and should be much less susceptible to operator error and gas-substrate interferences than impactors. The main advantage of each system, however, is the ability to collect large, sized, samples for subsequent analysis.

B. CYCLONE DESIGN

Our experience has shown that an empirical approach to cyclone design is useful if one has sufficient data. In this case several small cyclones had previously been calibrated and the dependence of the cut points upon the cyclone dimensions and sample aerosol flowrate determined. This experience was used to estimate the required dimensions for the new cyclones by relating their performance to that of prototypes, and in some cases to use the unmodified prototypes in the new systems.

In the case of specifications which were outside our range of "hands on" experience, designs were derived from equations found in the published literature. In addition to Chang's work there are several other papers which are useful in developing cyclone designs.[5,6,7,8] Figure 16 shows the nomenclature that is used in Lapple's equation to calculate the D_{50}, or cut point, for a cyclone of arbitrary size. Lapple's equation is:[9]

$$D_{50} = \sqrt{9\mu B_c/2\pi N_c V_c(\rho_s-\rho)}$$

where D_{50} = cyclone D_{50} (μm),

μ = gas viscosity (poise),

ρ_s = density of particle (gm/cm^3),

ρ = gas density (gm/cm^3),

N_c = number of turns made by gas stream in the cyclone body and cone,

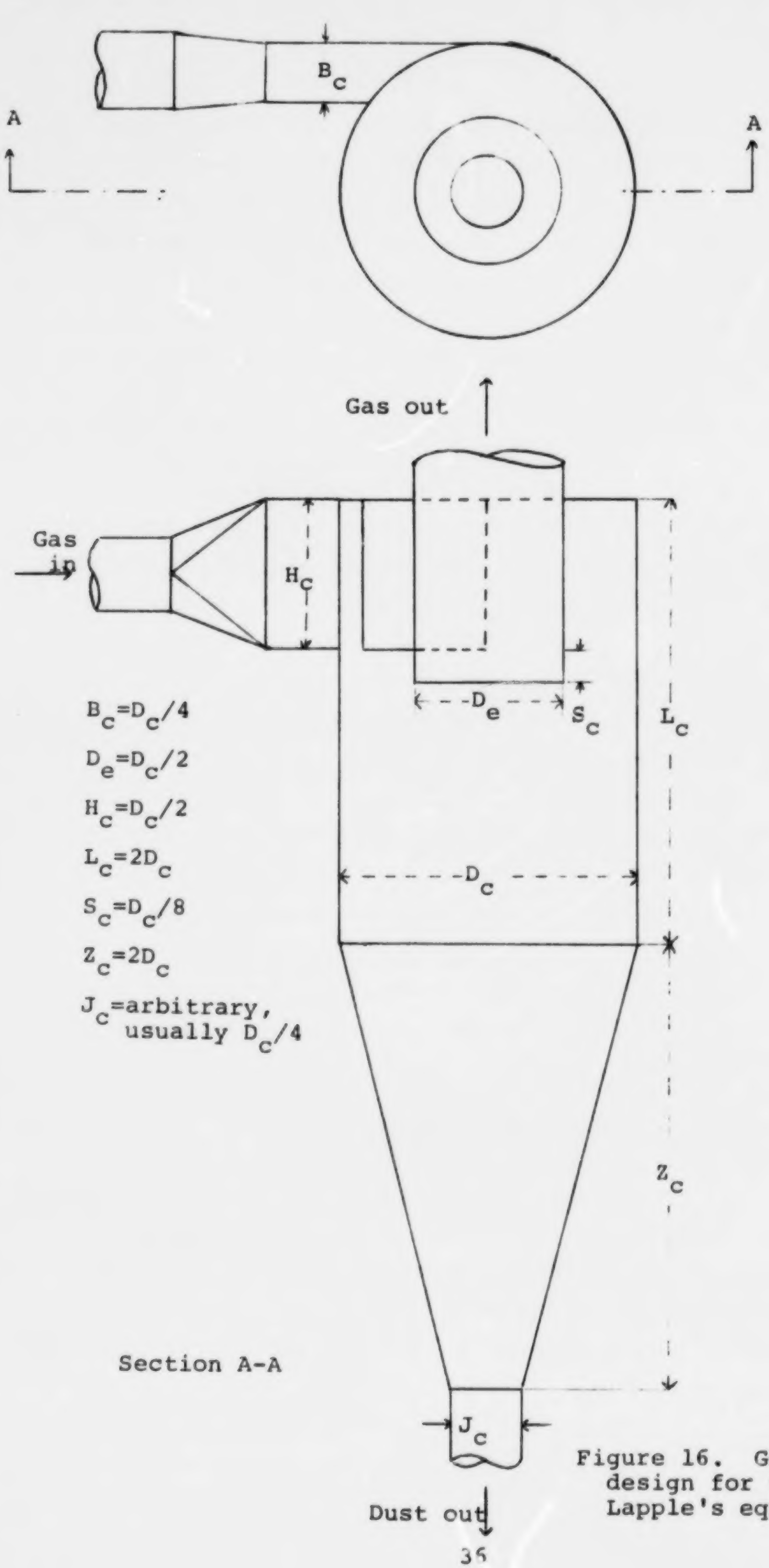

Figure 16. Generalized cyclone design for the application of Lapple's equation.

V_c = inlet air velocity (cm/sec), and
B_c = width of cyclone inlet (cm).

The square root relationship between D_{50} and V_c can be used to predict the cyclone performance over a wide range of flowrates if the cyclone has been calibrated at a known flowrate. In this case, we can rewrite Lapple's equation as

$$D_{50}(1) = \sqrt{CV_1}$$

where $D_{50}(1)$ = the cyclone cut point at flowrate 1,
C = the cyclone calibration constant, and
V_1 = aerosol flowrate 1.

Then the relationship between $D_{50}(1)$ and $D_{50}(2)$, the cut points at the two different flowrates, is

$$D_{50}(2) = D_{50}(1)\sqrt{\frac{V_1}{V_2}} \quad .$$

This relationship was verified experimentally and used to great advantage throughout this work.

To arrive at final designs for cyclones having the desired cut points three approaches were used: (1) Figure 16 and Lapple's equation were used, (2) Previously calibrated prototypes were used at various flowrates, and (3) Dimensions were selected by extrapolation for cyclones which were between sizes or related to the sizes of the prototypes which had been previously tested. Dimensioned shop drawings and calibration curves, if available, are shown in Appendix C for each cyclone studied.

C. ONE ACFM SERIES CYCLONE SAMPLING SYSTEM

A series cyclone system was developed during this study to satisfy the specific objectives of achieving longer sampling times in high grain loading situations and to collect gram quantities of size fractionated particulate for chemical analysis.

Several cyclone geometries were evaluated during these experiments. Because of the empiricism involved in the design procedures it was necessary to calibrate each cyclone and this was done using the vibrating orifice aerosol generator as a source of standard aerosols. Monodisperse ammonium fluorescein particles were sampled and the internal surfaces of the cyclones were then washed with 0.1N NH_4OH. The amount of particulate which had been caught on each surface was determined by using absorption spectroscopy to measure the concentration of ammonium fluorescein in the wash. Figure 17 shows calibration curves which were obtained in this manner for several cyclones which were considered as candidates for use in the 3-cyclone arrangement.

In conjunction with this calibration, a detailed study was done to determine the ultimate location of particles on the surfaces of the SRI-1 cyclone. These surfaces are the nozzle, body, cup, cap and outlet, and back-up filter. The results of this study are shown in Figure 18. As smaller particles are sampled, the amount collected by the back-up filter increases sharply for diameters of less than 4 microns. The nozzle and body both show single collection maxima at about 3 μm and then began to decrease as smaller particles were sampled. The cup shows a minimum at 3 μm and then a large increase in collection efficiency between 2 μm and 1 μm. For particles less than 1 μm in diameter, the cup collection efficiency decreases rapidly. The cap and outlet fractional deposition peaked at about 3 μm, decreased to 1 μm, then began to increase again as smaller particles were sampled.

For the system described here, cyclones SRI-5, SRI-1, and Chang's T2A were selected, with cut points of approximately 0.5 μm, 0.95 μm, and 2.6 μm, respectively, at a sample flowrate of one acfm and for particles having a density of 1.35 gm/cm^3. Different cut points could be achieved by the selection of other cyclones or

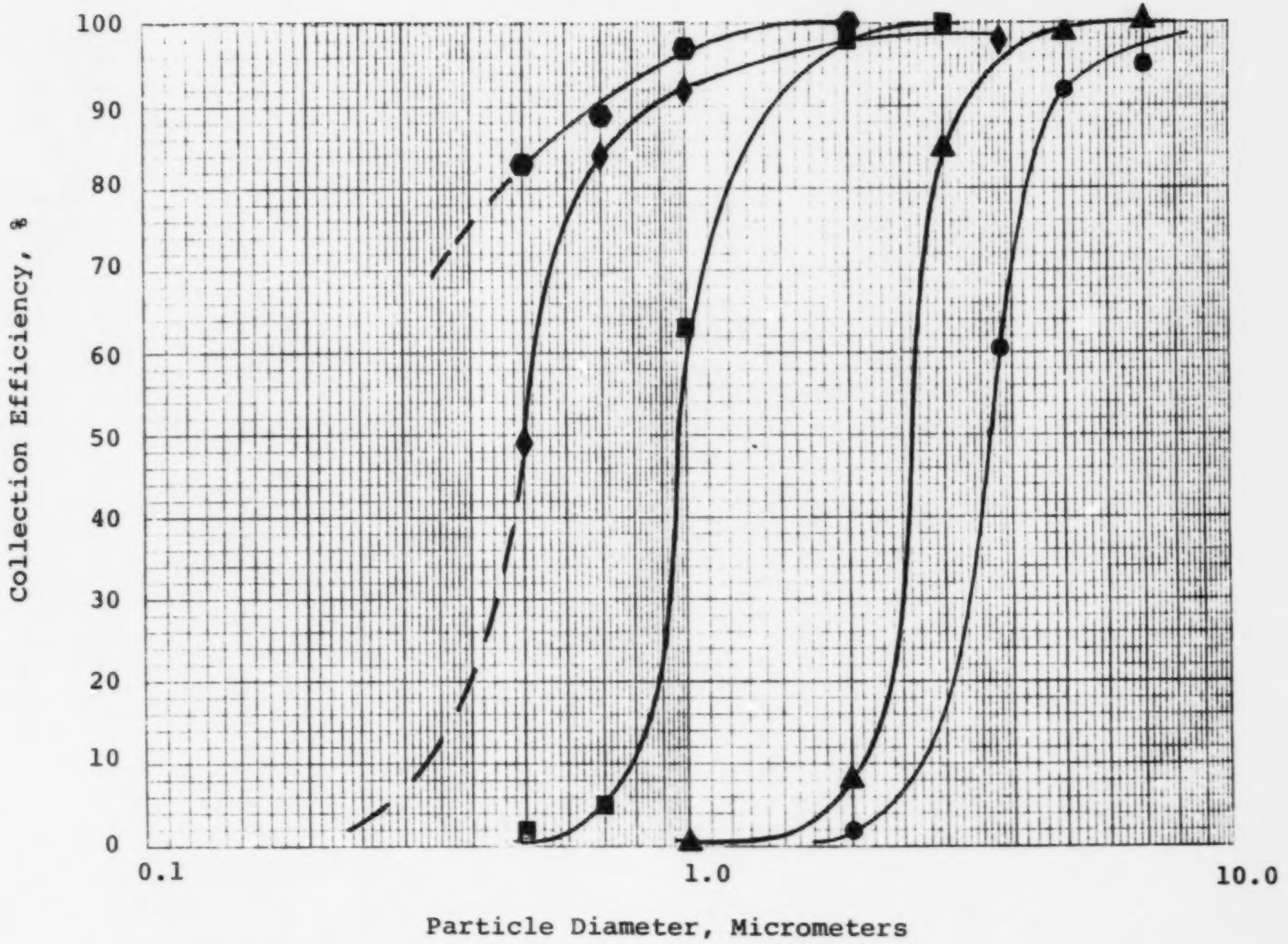

Figure 17. Collection efficiency vs. particle diameter

5 cyclones 1.0 acfm ρ=1.35 gm/cc 22°C, 29.5 "Hg

● SRI-3 ■ SRI-1 ⬣ "T1B"
▲ "T2A" ◆ SRI-5

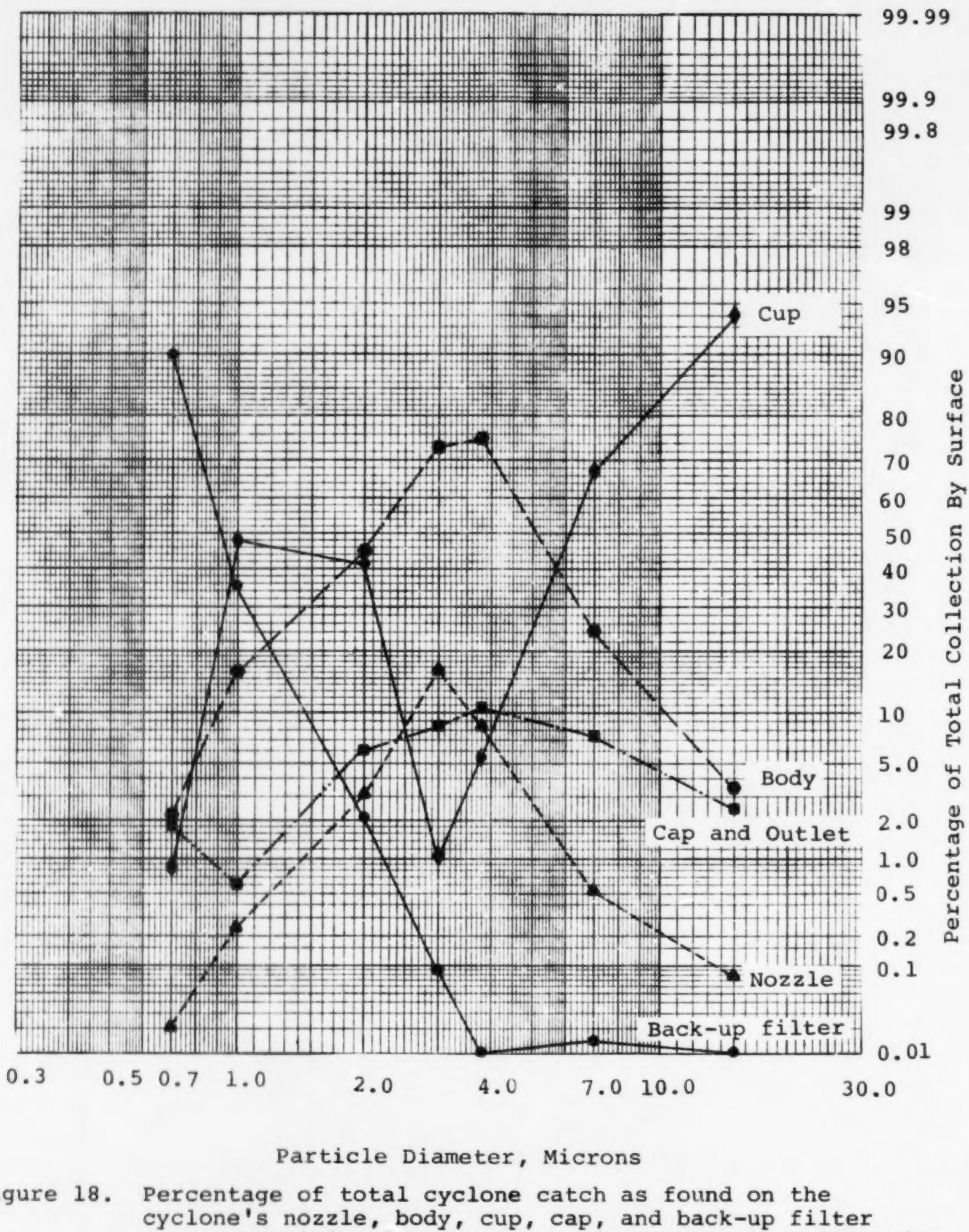

Figure 18. Percentage of total cyclone catch as found on the cyclone's nozzle, body, cup, cap, and back-up filter versus particle size. Based on data taken in calibration of the SRI-1 cyclone shown in Figure 12.

by changing the flowrate through the system. As a matter of fact, additional resolution could be obtained by sampling two or more times with different sample flowrates each time.

Figure 19 shows the final configuration of the one acfm series cyclone system. A "stacked" arrangement was used to join the cyclones in order to minimize the diameter required for sampling ports. This system can be used with six inch ports. A set of ten nozzles was fabricated to allow isokinetic sampling in flue gases with velocities from about 10 to 100 feet per second at the one acfm design flowrate. The cyclone cups and bodies of this prototype system are black anodized aluminum and the caps and inlet plates, which must withstand more stress, are made of stainless steel. More metal could be machined from the outer surfaces to lessen the total weight if a system made entirely of stainless steel were desirable.

Although the cyclones have been thoroughly calibrated using laboratory aerosols, field testing has been limited to date. A field test was conducted at a coal fired steam plant to determine the usefulness and accuracy of the one acfm series cyclone. The actual measurements were performed on the outlet side of an electrostatic precipitator, approximately 20 feet upstream of the stack. Gas velocities were on the order of 65 feet per second at the sampling location. Six inch ports were available and the series cyclone was held in a vertical orientation while sampling.* One test was performed during each of three days. The pertinent data are shown in Table III.

Concurrently during each series cyclone test a Brink Cascade impactor was used to sample the flue gas to give a comparison size distribution.

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*Treaftis and Tomb have shown that small cyclone performance is independent of orientation.[10]

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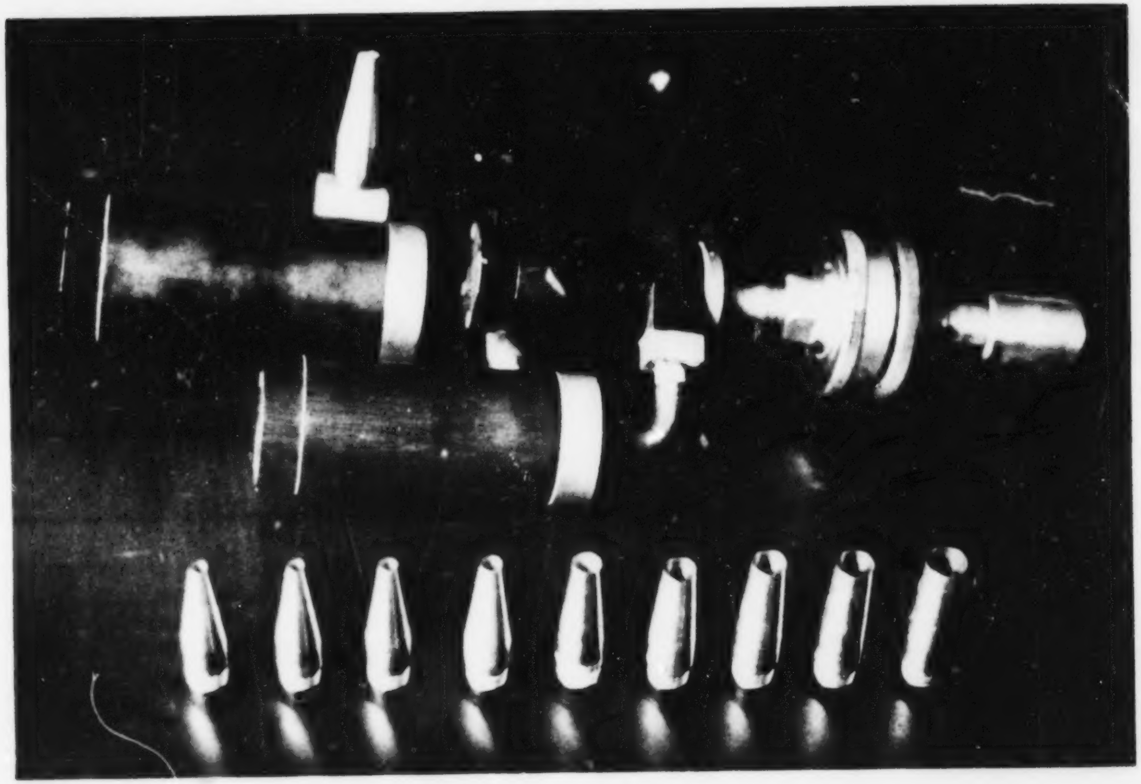


Figure 19. One ACFM series cyclone showing the three cyclones and Gelman back-up filter in the preferred orientation. The nozzles were designed for isokinetic sampling from 10 fps to 100 fps are also shown. The large cyclone is 4-3/4 inches long.

TABLE III

SERIES CYCLONE TEST DATA

TEST	1	2	3
DATE	3/11/75	3/12/75	3/13/75
Amb. Pres. ("Hg)	29.31	28.99	29.00
Stack Pres. ("H_2O)	-1.6	-1.2	-1.0
Gas Velocity (fps)	65	65	65
Imp. ΔP ("Hg)	3.2	3.1	3.7
Imp. Temp. (^oF)	290	280	300
G. M. or Orifice Temp. (^oF)	74	64	80
Flowrate (acfm)	.942	.908	.911
% H_2O	7.5	7.5	7.5
G. M. Vol. (ft^3)	20.893	26.650	41.200
Start Time	4:03	11:00	12:10
Duration (min.)	30	40	60
Nozzle Dia. (mm)	5.56	5.56	5.56
WEIGHT GAIN (mg)			
Cyclone 1	777.62	483.14	4276.21
Cyclone 2	77.24	77.04	584.90
Cyclone 3	18.86	19.70	123.76
Filter	5.02	4.96	19.56

Actual sampling with the series cyclone was very simple. The flowrate was maintained at its proper value using a dry gas meter. The cyclone was allowed to warm up for 45 minutes before sampling began and a nozzle was chosen to obtain isokinetic sampling. For the Brink Cascade Impactor a 2.5 mm nozzle was the smallest one available. At the 0.03 acfm flowrate a 1 mm nozzle would have been necessary for isokinetic sampling. Because of this, the larger particles were oversampled and a higher than normal grain loading was indicated by the Brink, although the small particle end of the distribution was apparently not affected by the nonisokinetic sampling. Figures 20, 21, and 22 show the results of the three tests. In each figure the series cyclone and Brink agree well up to about 3 microns. Beyond this point they diverge due to the anisokineticity of the Brink sample.

Figures 23 and 24 show micrographs of the material collected in each cyclone and on the backup filter. Very effective size segregation by the cyclones is clearly shown in these figures.

Great care is needed in cleaning the cyclones to assure that dust is not lost. Cleaning the elbows connecting the cyclones is important because a significant amount of material collects there. The cyclone was brushed out to recover most of the collected dust, although small amounts of residual dust remained on the brush and cyclone walls. In these tests, the amount of dust lost was insignificant in comparison to the large amount of dust collected. This could represent a problem at sites where smaller samples are collected.

These preliminary results indicate that the series cyclone concept is very useful as a mechanism for obtaining particle size distribution data and size fractionated samples, and that the system is convenient to operate and somewhat more foolproof than cascade impactors.

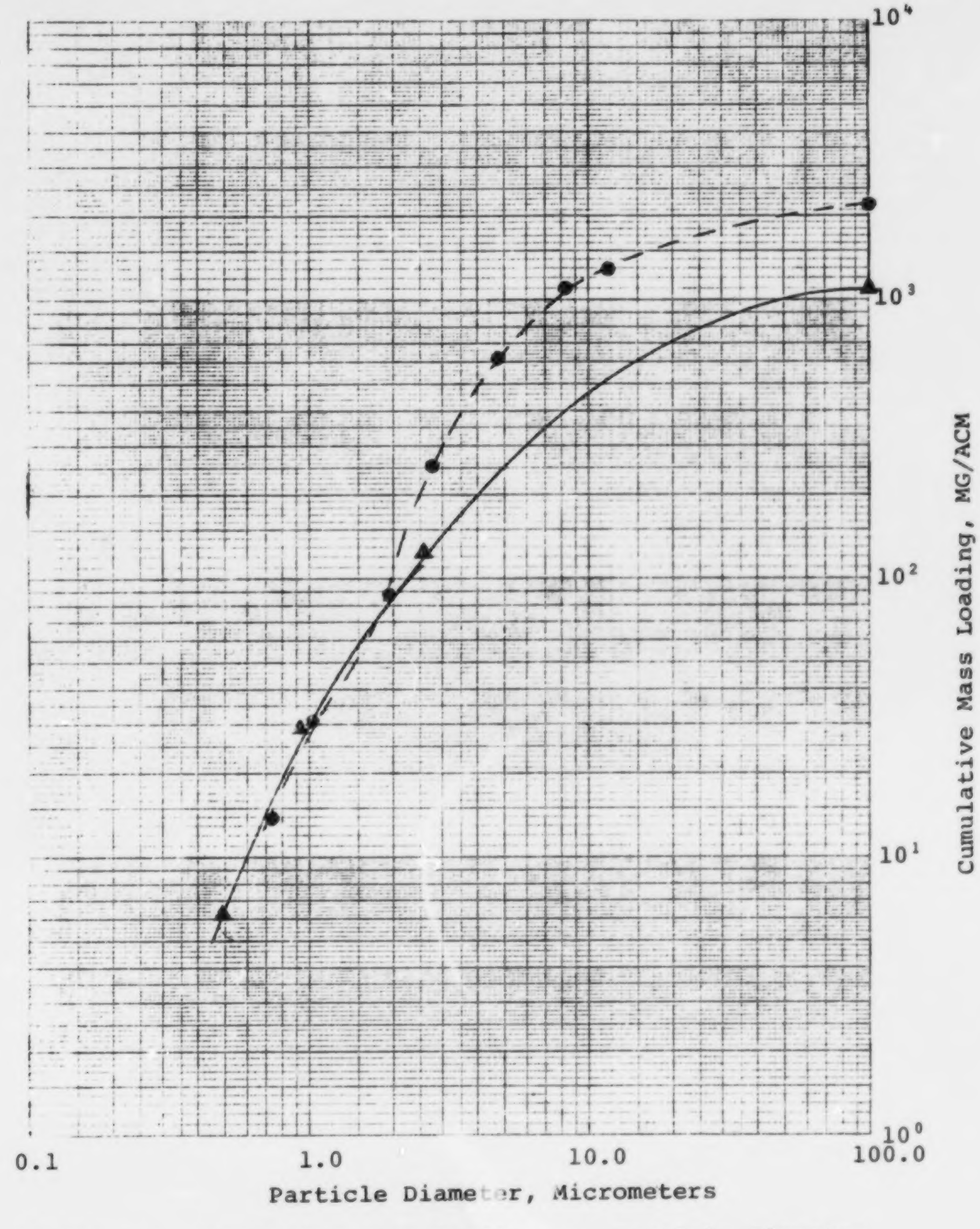


Figure 20. Cumulative mass loading vs. Particle diameter
March 11, 1975

— ● — Brink Cascade Impactor, 0.03 ACFM

—▲— Series Cyclone, 1.0 ACFM

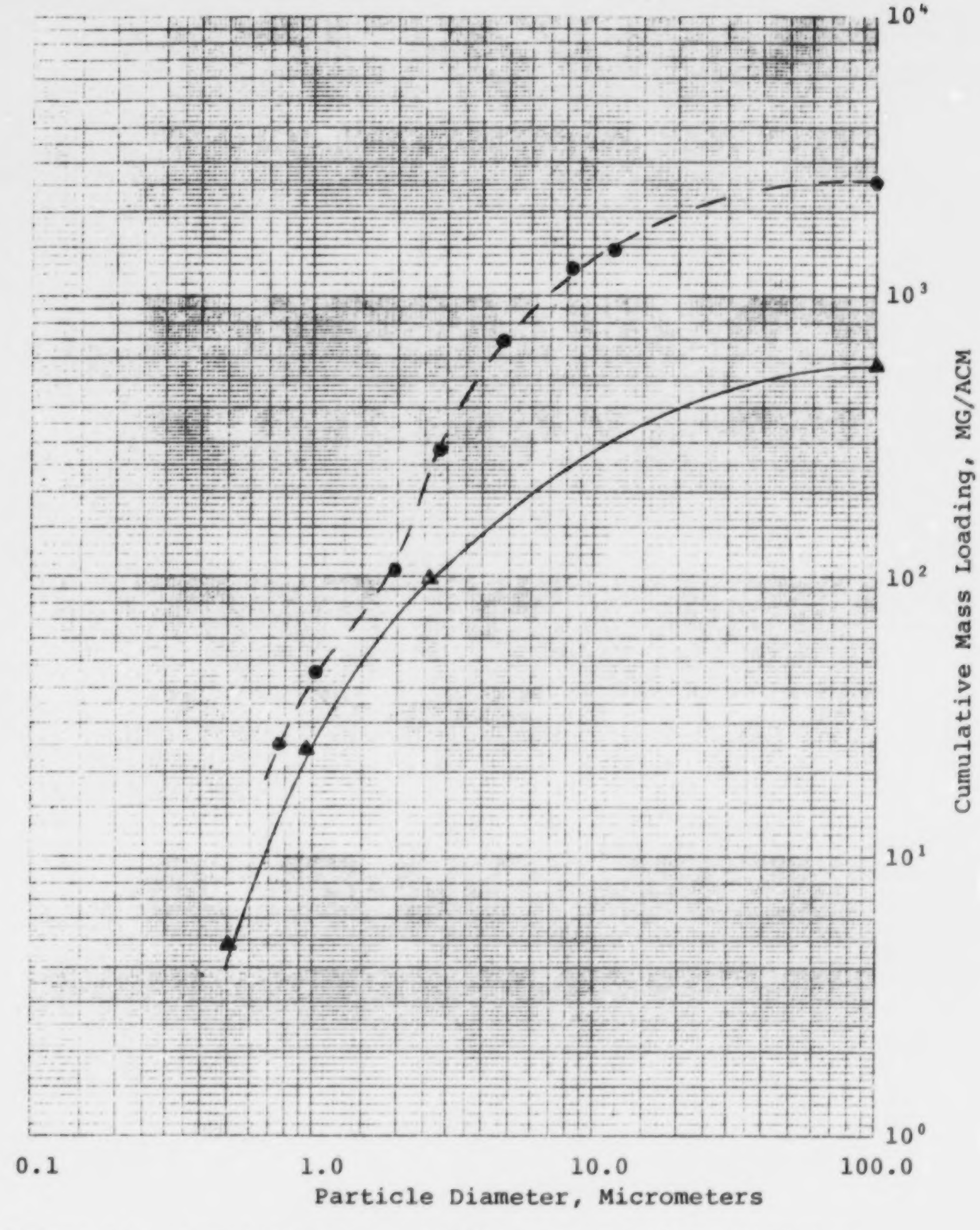


Figure 21. Cumulative mass loading vs. Particle diameter March 12, 1975

— ● —Brink Cascade Impactor, 0.03 ACFM

—▲— Series Cyclone, 1.0 ACFM

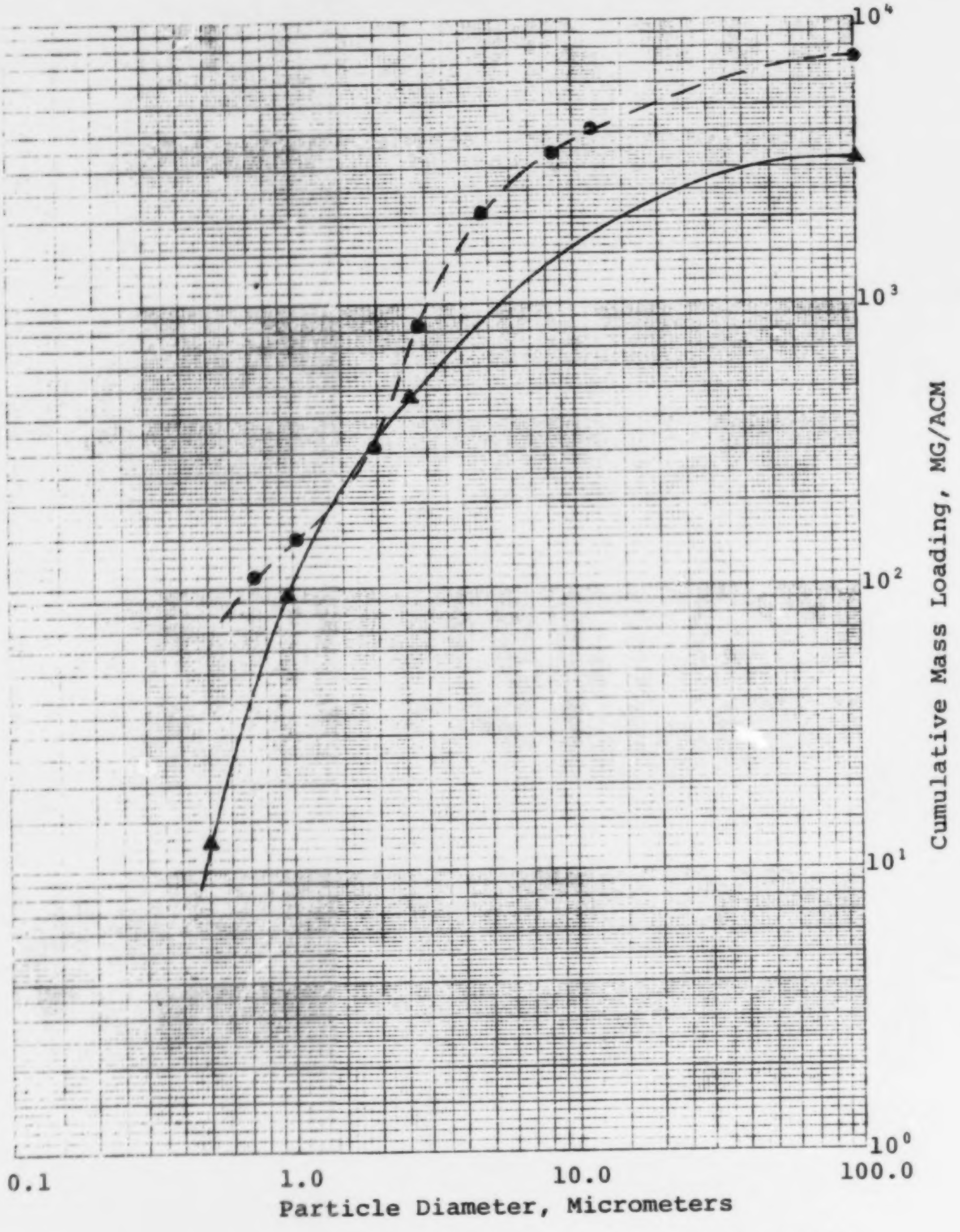
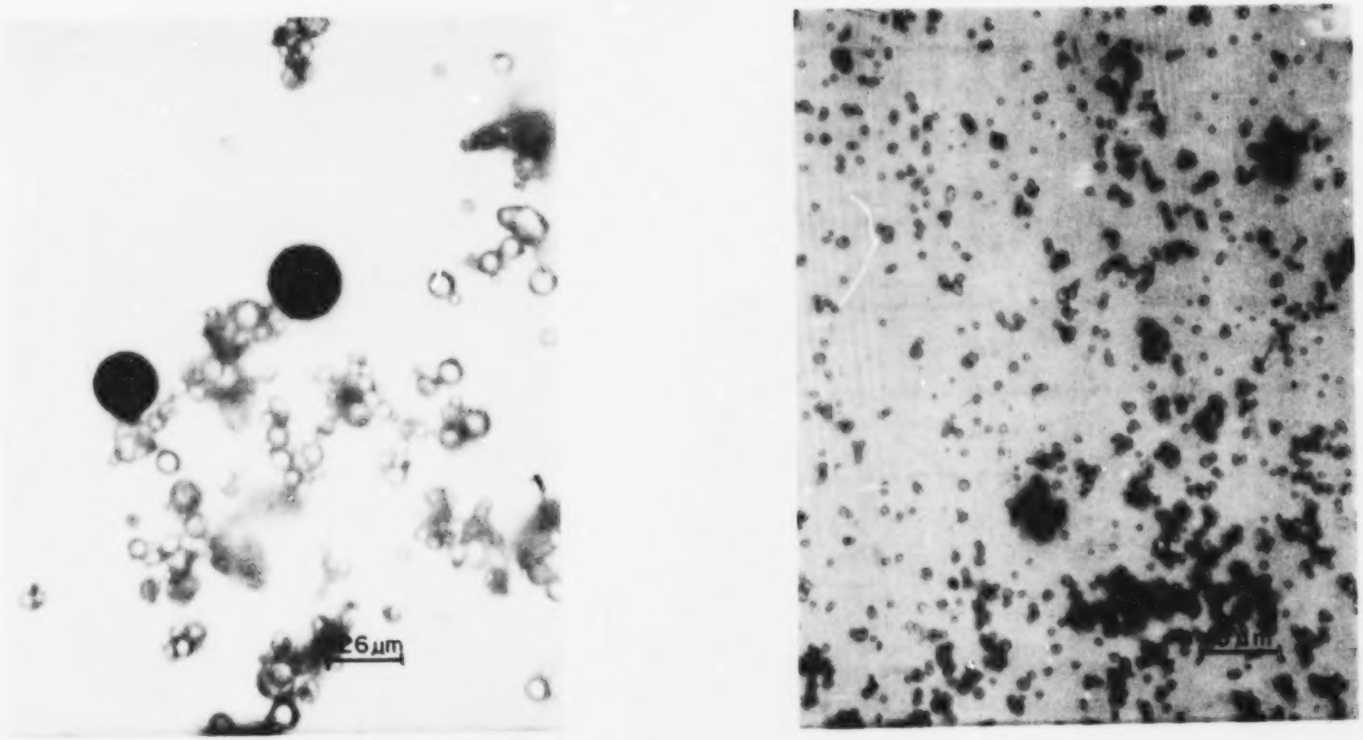


Figure 22. Cumulative mass loading vs. Particle diameter
March 13, 1975

— —●— —Brink Cascade Impactor, 0.03 ACFM

——▲——Series Cyclone, 1.0 ACFM



Cyclone 1

D_{50} = 2.5 μm

Cyclone 2

D_{50} = 1.0 μm

Figure 23. Photomicrographs of cyclone catches acquired at Bull Run Steam Plant.

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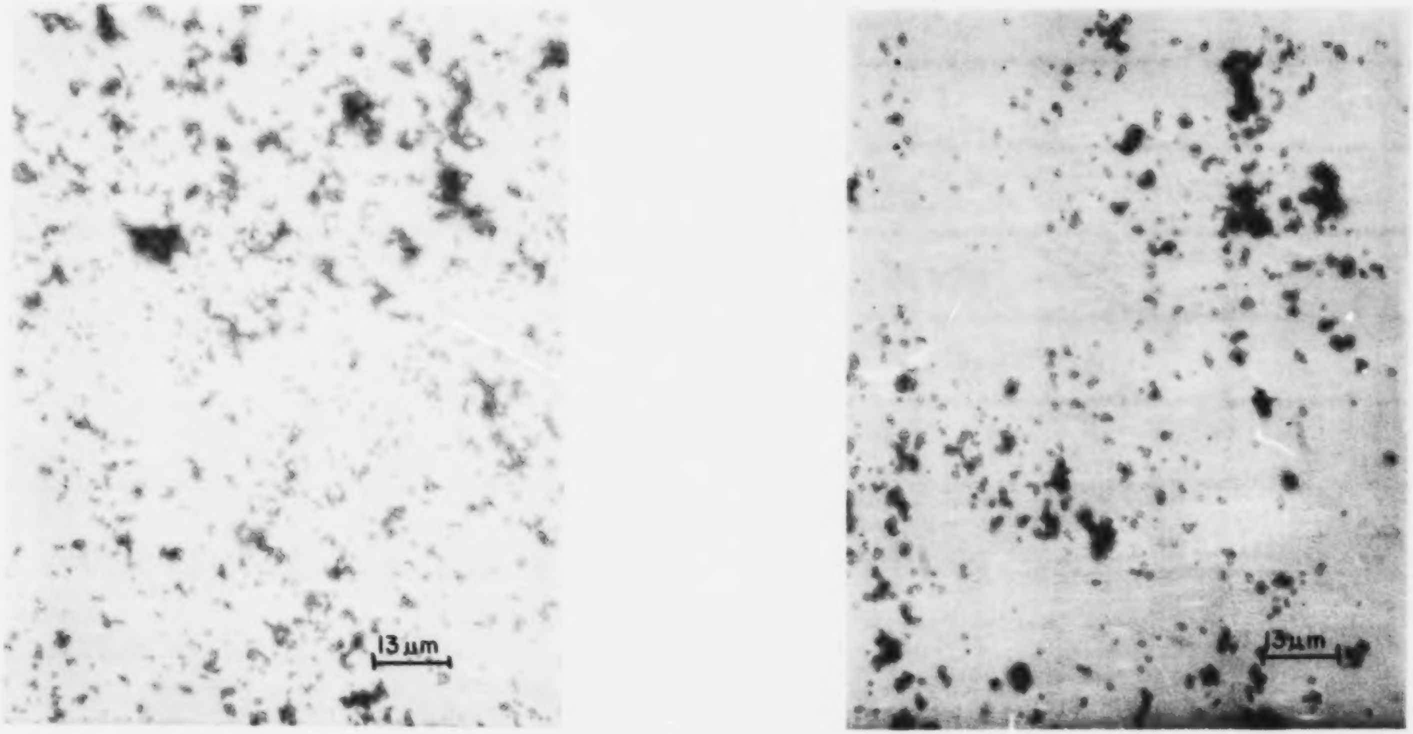

Back-Up Filter

Cyclone 3

$D_{50} = 0.5\ \mu m$

Figure 24. Photomicrographs of cyclone and back-up filter catches acquired at Bull Run Steam Plant.

SECTION IV

APPENDICES

APPENDIX A - Andersen Impactor Weight Loss Study

APPENDIX B - Impactor Glass Fiber Substrate Weight Gains

APPENDIX C - Cyclone Design

APPENDIX D - Conversion Table for Units

APPENDIX A

ANDERSEN FILTER SUBSTRATE WEIGHT LOSS STUDY

This study was undertaken to determine if weight losses from the fiber filter substrates of the Andersen Impactor were significant and to what extent they might affect field test measurements. A procedure was set up to check for errors in the mechanics of the weighing, moisture absorption by the substrates, errors due to handling, and errors resulting from running an impactor. These will be explained in detail later.

The filter substrates for the Andersen Impactors, with the exception of the back-up filters, were baked for approximately 18 hrs in an oven at a temperature of 240°C. The back-up filters were baked for about 6 hrs at the same temperature. The substrates were from normal Andersen substrate stock. The back-up filters were cut from glass fiber filter stock. Mine Safety Appliance No. CT-75428.

After all substrates and filters had been baked, they were allowed to cool to ambient temperature in room air. They then were left sitting out for 4 days at room temperature and humidity while their foil holders were cut. After being folded and placed in the foil holders, the substrates, including foil holder, were weighed. The process of placing the substrates in the foils and then weighing them took 2 days, making a total of 6 days elapsed time from the baking procedure. All substrates were then placed in desiccators.

The balance used in the study was a Cahn Model G-2 Electrobalance. The total weight of the substrates and foils was greater than 200 mg but this scale was used with counterweights (tare weights) for improved accuracy. To keep moisture at a minimum, the weighing chamber was loaded with a small pan containing Drierite, anhydrous $CaSO_4$. This is our normal procedure in weighing Andersen substrates.

The average weights for the Andersen glass fiber substrates and back-up filters were also measured so that the weight losses could be evaluated relative to this total weight. Due to the design of the Andersen Impactor, the filter substrates alternate in pattern from stage 1 to stage 8; stage filters being alike for stages 1, 3, 5, and 7, but different for stages 2, 4, 6, and 8. To obtain an average weight, 50 substrate filters of the odd type (1, 3, 5, 7), 50 of the even type (2, 4, 6, 8), and 50 back-up filters were baked at 240°C for 6 hours, desiccated for 18 hours, and then weighed on a Mettler Gram-atic balance. The average weights are:

Odd Filter Stage Substrates (1, 3, 5, 7)	189.54 mg average,
Even Filter Stage Substrates (2, 4, 6, 8)	178.92 mg average, &
Back-up Filter	215.04 mg average.

Weighing-Balance Errors and Moisture Absorption Errors

Three sets of the substrates, Nos. 13N, 15N, and 16N, were used to check the possibility of errors being made just in the process of weighing the substrates. Also, this was a check on the reproducibility of the balance in weighing an object. In addition to sets 13N, 15N, and 16N, two stainless steel ferrules and one flat washer were included in the weighing as standards, since these should neither lose nor gain significant mass due to absorption. They were cleaned in benzene to remove any grease and kept in clean containers in a desiccator throughout the test. Tweezers were always used in handling the ferrules, the washer, and the foil-wrapped substrates.

The results of the ferrule and washer weighings are given in Table A-1. Approximately one weighing of each was made each

TABLE A-1

STEEL FERRULE AND WASHER WEIGHT CHANGES UPON DESICCATION

	Initial Weight, mg	Cumulative Hours of Desiccation									
		6	24	30	48	54	72	78	96	120	144
A	494.12	+.02	.00	+.02	.00	+.02	.02	.00	.00	+.02	+.02
B	422.50	.00	.02	.00	.00	.00	.02	.02	+.02	.02	.00
C	413.80	.00	.02	.02	.00	.02	+.02	.02	+.02	.02	+.02

Weight change in mg as compared to initial weight after indicated number of hours of desiccation.

A & B are stainless steel Swagelok ferrules; C is a zinc-plated steel washer.

All weight changes are negative unless otherwise noted.

day during the study. (All weights in all tables are negative except those preceded by a + sign). The two ferrules were made of 316 stainless steel and are listed as "A" and "B" in the table. The washer was made of zinc-plated steel and is listed as "C". The true weight of A, B, and C can be derived since the tare weight used with the Cahn balance was weighed also. Its weight was 366.7 mg, as weighed on a Mettler Gram-atic balance.

$$\text{True weight} = \left[\text{Cahn reading} \times 200 + 366.7\right] \text{mg}$$

The "Cahn reading" is the reading taken from the mass dial as a fraction of full scale, which is unity; 200 is the range multiplier; and 366.7 is the tare weight correction. Using a mass reading of 0.4321 as an example:

$$\left[0.4321 \times 200 + 366.7\right] \text{mg} = 453.1 \text{ mg}$$

True weights were not generally calculated because weight losses could be monitored by differences of direct readings on the Cahn.

The substrate sets 13N, 15N, and 16N were the control group of substrates. They were weighed periodically while the other tests were being conducted. They served as a check on desiccation losses, balance calibration, and zero shift. These sets remained wrapped in their foil covers throughout the tests to avoid any loss of the filter material. The results of weighing these sets are shown in Table A-2. The amount of desiccation prior to each weighing is indicated in the table.

The table is structured as it is because Andersen substrates are of two types, varying between even and odd impactor plates.

TABLE A-2

ANDERSEN SUBSTRATE CUMULATIVE WEIGHT CHANGE DUE TO DESICCATION
(SETS 13N, 15N, 16N)

		Desiccation Period					
	Initial	6 hrs	24 hrs	48 hrs	72 hrs	96 hrs	120 hrs
Odd Numbered Stage Substrates:							
Average	-	0.12 mg	0.15	0.14	0.14	0.15	0.15
σ	-	0.03 mg	0.03	0.02	0.03	0.02	0.02
No. of Filters	-	12	12	12	12	12	12
Even Numbered Stage Substrates:							
Average	-	0.12 mg	0.15	0.14	0.14	0.15	0.16
σ	-	0.04	0.03	0.02	0.02	0.03	0.02
No. of Filters	-	12	12	12	12	12	12
Back-Up Filters:							
Average	-	0.05 mg	0.09	0.09	0.09	0.07	0.10
σ	-	(0.01 mg)	(0.03)	(0.02)	(0.01)	(0.02)	(0.03)
No. of Filters	-	3	3	3	3	3	3

Cumulative weight change as compared to initial weight after indicated number of hours of desiccation.

All weight changes are negative unless otherwise noted.

Parentheses indicate loss of accuracy due to insufficient data.

The substrates are cut to fit the impactor plate without obstructing the jets. Any difference in surface area of the filter might cause a different evaporation amount. The back-up filter is also separated from the even and odd substrates.

Table A-3 gives the raw data for each set of substrates by stage. Table A-4 indicates the moisture pickup of substrates which had been baked and desiccated as previously described. Three back-up filters were used, and instead of Drierite, a container of water was placed in the balance weighing chamber to give maximum humidity. Before the test, the balance was zeroed and calibrated.

Handling Losses

Handling losses in this case mean losses occurring in the process of loading and unloading an impactor. The substrates were taken from the foil covers and loaded into an impactor just as if it were about to be run; but immediately after assembling it, the impactor was unloaded and the substrates placed in the foil covers.

Six sets of substrates were used. Three sets (10N, 11N, 12N) were treated entirely as typical substrates for a normal run. The other three were cleaned. Each filter substrate was carefully checked for loose fiber pieces, which were removed, and then each filter was blown off with dustless freon. These were designated as the "clean" substrates (7N, 8N, 9N).

All six sets were desiccated for 48 hrs, weighed, loaded into impactors, unloaded, and then placed in the desiccator for 48 additional hours.

During the unloading process, the jet plates were brushed down to remove any bits of fiber which remained on them. Any

TABLE A-3

CUMULATIVE CHANGES IN WEIGHT DUE TO DESICCATION FOR ANDERSEN SUBSTRATES BY INDIVIDUAL SET

		Cumulative Desiccation Period					
		6 hrs	24 hrs	48 hrs	72 hrs	96 hrs	120 hrs
Set 13N							
	1	0.10 mg	0.15 mg	0.12 mg	0.10 mg	0.12 mg	0.14 mg
	2	0.04	0.12	0.10	0.12	0.10	0.14
	3	0.10	0.12	0.12	0.14	0.12	0.14
	4	0.08	0.16	0.14	0.14	0.16	0.16
	5	0.10	0.16	0.18	0.18	0.18	0.20
	6	0.10	0.16	0.16	0.16	0.18	0.18
	7	0.08	0.12	0.14	0.14	0.12	0.14
	8	0.10	0.12	0.12	0.12	0.10	0.14
	F	0.06	0.08	0.10	0.08	0.10	0.12
Set 15N							
	1	0.16	0.16	0.14	0.14	0.16	0.16
	2	0.14	0.16	0.14	0.16	0.18	0.18
	3	0.10	0.12	0.12	0.10	0.12	0.12
	4	0.14	0.14	0.14	0.12	0.14	0.14
	5	0.16	0.16	0.18	0.16	0.16	0.18
	6	0.14	0.12	0.12	0.12	0.12	0.14
	7	0.16	0.16	0.14	0.14	0.12	0.16
	8	0.14	0.14	0.16	0.14	0.16	0.16
	F	0.06	0.06	0.06	0.08	0.06	0.06
Set 16N							
	1	0.14	0.20	0.14	0.14	0.16	0.16
	2	0.16	0.20	0.18	0.18	0.18	0.20
	3	0.12	0.18	0.16	0.14	0.18	0.16
	4	0.16	0.18	0.16	0.16	0.18	0.16
	5	0.14	0.20	0.18	0.18	0.16	0.12
	6	0.10	0.10	0.12	0.10	0.12	0.12
	7	0.10	0.14	0.12	0.12	0.16	0.14
	8	0.08	0.18	0.12	0.12	0.16	0.14
	F	0.04	0.12	0.10	0.10	0.06	0.12

All weight changes are negative unless otherwise noted.

TABLE A-4

MOISTURE ABSORPTION BY THREE ANDERSEN BACK-UP FILTERS

Elapsed Time (min)	Cumulative Weight Changes, mg		
	#1	#2	#3
0	-	-	-
5	+.10	+.08	+.08
10	+.10	+.08	+.08
15	+.12	+.12	+.14
20	+.12	+.12	+.14
25	+.12	+.12	+.14
30	+.12	+.12	+.14

loose fiber was placed with the substrate nearest it. Sets 9N and 11N which were loaded into Andersen No.507 showed signs of the substrates being partially cut through by the metal o-rings. These two sets were the only ones with noticeable pieces of fiber left on the jet stages, which were brushed onto corresponding substrates.

Table A-5 gives average losses of the cleaned-up substrates. Table A-6 gives the same for the normal substrates. Tables A-7 and A-8 give individual stage losses for all six sets.

Running Losses

Six sets were used for determination of weight change while sampling filtered air. They were treated as normal substrates in loading them into the foil covers. No special cleaning of the filters was done. All sets were desiccated for 48 hours.

Three of the sets (4N, 5N, 6N) were loaded into impactors after desiccation and the impactors were run at 0.5 acfm for 6 hrs at room temperature, 24° C. A Gelman 47-mm filter holder and filter were attached to the inlet of the impactors to insure that clean air was sampled.

The other three sets (1N, 2N, 3N) were set up in the same way and run at 0.5 acfm for 6 hrs in an oven at 120°C.

When these sets of substrates were unloaded, the same brushing technique as described above was used. The substrates from the impactors run at room temperature were similar to those that had just been loaded and unloaded. The Andersen No. 507 impactor showed slight gasket cuts on several of the substrates. Andersens No. 229 and 231 had no cut substrates, but were crimped as required for a good seal.

TABLE A-5

DESICCATION AND HANDLING WEIGHT CHANGE OF "CLEAN" ANDERSEN SUBSTRATES (7N, 8N, 9N)

Desiccation Weight Change	Average	σ	Number in Average
Odd numbered substrates	0.02 mg	0.06 mg	12
Even numbered substrates	0.10	0.04	12
Back-up filters	+0.01	(0.05)	3
Handling Weight Change			
Odd numbered substrates	0.06 mg	0.04 mg	12
Even numbered substrates	0.09	0.04	12
Back-up filters	0.04	(0.06)	3
Handling Weight Change by Stage			
Stage			
1	0.03 mg	(0.04) mg	3
2	0.08	(0.02)	3
3	0.05	(0.02)	3
4	0.09	(0.03)	3
5	0.09	(0.05)	3
6	0.11	(0.01)	3
7	0.07	(0.03)	3
8	0.08	(0.05)	3
F	0.04	(0.06)	3

Numbers in parentheses indicate insufficient data for accurate σ.

All weight changes are negative unless otherwise noted.

TABLE A-6

DESICCATION AND HANDLING WEIGHT CHANGE OF "NORMAL" ANDERSEN SUBSTRATES (10N, 11N, 12N)

Desiccation Weight Change	Average	σ	Number in Average
Odd numbered substrates	0.02	0.04	12
Even numbered substrates	0.00	0.03	12
Back-up filters	0.08	(0.07)	3
Handling Weight Change			
Odd numbered substrates	0.06	0.06	12
Even numbered substrates	0.04	0.04	12
Back-up filters	+0.01	(0.08)	3
Handling Weight Change by Stage			
Stage			
1	0.10	(0.05)	3
2	0.07	(0.05)	3
3	0.08	(0.02)	3
4	0.05	(0.07)	3
5	0.01	(0.02)	3
6	0.01	(0.02)	3
7	0.03	(0.08)	3
8	0.03	(0.02)	3
F	+0.01	(0.08)	3

Numbers in parentheses indicate insufficient data for accurate σ.

All weight changes are negative unless otherwise noted.

TABLE A-7

DESICCATION AND HANDLING WEIGHT CHANGE OF "CLEAN" ANDERSEN SUBSTRATES BY SETS

	Weight Change During Desiccation	Weight Change After Impactor Loading
Set 7N Andersen 229		
1	0.12 mg	0.00 mg
2	0.18	0.06
3	0.02	0.04
4	0.16	0.01
5	0.02	0.08
6	0.08	0.12
7	0.02	0.04
8	0.14	0.04
F	0.04	+0.02
Set 8N Andersen 231		
1	0.06	0.08
2	0.10	0.10
3	0.04	0.04
4	0.12	0.12
5	0.00	0.14
6	0.06	0.12
7	0.06	0.06
8	0.06	0.06
F	+0.02	0.04
Set 9N Andersen 507		
1	+0.04	0.02
2	0.06	0.08
3	0.00	0.08
4	0.06	0.14
5	+0.02	0.04
6	0.10	0.10
7	+0.10	0.10
8	0.04	0.14
F	+0.06	0.10

All weight changes are negative unless otherwise noted.

TABLE A-8

DESICCATION AND HANDLING WEIGHT CHANGES OF "NORMAL" ANDERSEN SUBSTRATES BY SET

	Weight Change During Desiccation	Weight Change After Impactor Loading
Set 10N Andersen 229		
1	0.00 mg	0.12 mg
2	+0.04	0.12
3	0.02	0.10
4	0.00	0.12
5	+0.02	0.04
6	+0.06	0.04
7	+0.06	0.12
8	+0.02	0.06
F	0.00	0.08
Set 11N Andersen 507		
1	0.04 mg	0.14 mg
2	+0.02	0.04
3	0.00	0.08
4	0.00	0.04
5	0.04	0.00
6	0.02	0.00
7	0.00	0.02
8	0.04	0.02
F	0.10	+0.06
Set 12N Andersen 231		
1	0.10 mg	0.04 mg
2	0.02	0.04
3	0.04	0.06
4	0.02	+0.02
5	0.02	0.00
6	0.02	0.00
7	0.02	+0.04
8	0.00	0.02
F	0.14	+0.04

All weight changes are negative unless otherwise noted.

The substrates run at 120°C showed more cutting. Again, Andersen No. 507 had substrates which were cut by the seals but slightly more severely. There were more pieces of fiber on the jet stage than previously. Substrates from Andersens No. 229 and 231 this time showed slight cuts in some of the stages. This may have been due to heating the impactor, or possibly to overtightening of the impactors, although an attempt was made to tighten them equally each time.

After sampling filtered air for 6 hrs, each set was unloaded, brushed, foiled, and desiccated for 48 hours before weighing. The results are shown in Tables A-9 through A-12.

Miscellaneous

In Table A-13, the results of two blank sets of substrates loaded normally and run under stack sampling conditions at an aluminum reduction plant with a Gelman filter in front of the impactor, are given. The stack temperature was 125°F and the running times are listed in the table. Also shown is the average of a blank set run at a hot side precipitator on a coal-fired boiler.

For comparison and to gauge the significance of impactor weight losses, Table A-14 includes some averages of typical Andersen Impactor stage net weight changes, including possible filter weight loss, observed in sampling several types of industrial particulate sources.

Also investigated was the possibility of using Teflon filter membranes as substrates. The type of Teflon filter used was

TABLE A-9

DESICCATION AND SAMPLING WEIGHT CHANGE OF ANDERSEN SUBSTRATES (4N, 5N, 6N) AFTER SAMPLING FILTERED AIR AT 0.5 ACFM FOR SIX HOURS AT 24°C

Weight Change During Desiccation	Average	σ	Number in Average
Odd numbered substrates	0.16 mg	0.05	12
Even numbered substrates	0.14	0.03	12
Back-up filters	0.17	(0.03)	3
Weight Changes Due to Sampling			
Substrates 1-4 average	0.06 mg	0.03	12
Substrates 5-8 average	0.07	0.03	12
Odd numbered substrates	0.07	0.03	12
Even numbered substrates	0.06	0.02	12
Back-up filters	+0.03	(0.03)	3
Sampling Weight Change by Stage			
Stage			
1	0.08 mg	(0.02)	3
2	0.06	(0.02)	3
3	0.05	(0.05)	3
4	0.05	(0.03)	3
5	0.06	(0.02)	3
6	0.06	(0.02)	3
7	0.07	(0.03)	3
8	0.07	(0.03)	3
F	+0.03	(0.03)	3

All weight changes are negative unless otherwise noted.

Parentheses indicate loss of accuracy due to insufficient data.

TABLE A-10

DESICCATION AND SAMPLING WEIGHT CHANGE OF ANDERSEN SUBSTRATES (1N, 2N, 3N) AFTER SAMPLING FILTERED AIR AT 0.5 ACFM FOR SIX HOURS AT 120°C

Weight Change During Desiccation	Average	σ	Number in Average
Odd numbered substrates	0.14 mg	0.04	12
Even numbered substrates	0.15	0.05	12
Back-up filters	0.15	(0.06)	3
Weight Change Due to Sampling			
Substrates 1-4 average	0.15	0.04	12
Substrates 5-8	0.17	0.04	12
Odd numbered substrates	0.17	0.04	12
Even numbered substrates	0.15	0.04	12
Back-up filters	+0.03	(0.08)	3
Sampling Weight Change by Stage			
Stage			
1	0.15	(0.01)	3
2	0.11	(0.02)	3
3	0.17	(0.04)	3
4	0.13	(0.02)	3
5	0.14	(0.00)	3
6	0.17	(0.02)	3
7	0.19	(0.06)	3
8	0.19	(0.01)	3
F	+0.03	(0.08)	3

All weight changes are negative unless otherwise noted.

Parentheses indicate loss of accuracy due to insufficient data.

TABLE A-11

DESICCATION AND SAMPLING WEIGHT CHANGES OF ANDERSEN SUBSTRATES BY SETTING AFTER SAMPLING FILTERED AIR AT 0.5 ACFM FOR SIX HOURS AT 24°C

	Weight Change During Desiccation	Weight Change Due to Sampling
Set 4N Andersen 229		
1	0.20 mg	0.08 mg
2	0.12	0.04
3	0.16	0.08
4	0.16	0.06
5	0.08	0.08
6	0.08	0.08
7	0.04	0.12
8	0.12	0.08
F	0.14	0.00
Set 5N Andersen 231		
1	0.22 mg	0.06 mg
2	0.12	0.08
3	0.18	0.00
4	0.16	0.02
5	0.18	0.06
6	0.12	0.06
7	0.18	0.08
8	0.18	0.10
F	0.20	+0.04
Set 6N Andersen 507		
1	0.20 mg	0.10 mg
2	0.18	0.06
3	0.18	0.08
4	0.16	0.08
5	0.12	0.04
6	0.12	0.04
7	0.18	0.10
8	0.14	0.04
F	0.18	+0.06

All weight changes are negative unless otherwise noted.

TABLE A-12

DESICCATION AND SAMPLING WEIGHT CHANGES OF ANDERSEN SUBSTRATES BY SET AFTER SAMPLING FILTERED AIR AT 0.5 ACFM FOR SIX HOURS AT 120°C

	Weight Change During Desiccation	Weight Change Due to Sampling
Set 1N Andersen 229		
1	0.14 mg	0.16 mg
2	0.12	0.10
3	0.12	0.16
4	0.18	0.10
5	0.16	0.14
6	0.16	0.14
7	0.14	0.24
8	0.14	0.18
F	0.10	+0.06
Set 2N Andersen 231		
1	0.10 mg	0.14 mg
2	0.10	0.14
3	0.06	0.14
4	0.12	0.14
5	0.16	0.14
6	0.10	0.18
7	0.08	0.12
8	0.10	0.18
F	0.12	+0.10
Set 3N Andersen 507		
1	0.16 mg	0.20 mg
2	0.20	0.10
3	0.16	0.22
4	0.20	0.14
5	0.18	0.14
6	0.22	0.18
7	0.22	0.22
8	0.20	2.20
F	0.22	0.06

All weight changes are negative unless otherwise noted.

TABLE A-13

WEIGHT CHANGES OF ANDERSEN SUBSTRATE AFTER SAMPLING FILTERED EFFLUENT FROM A WET PRECIPITATOR AT AN ALUMINUM REDUCTION PLANT. 125°F GAS TEMPERATURE

	Sampling Time	
Stage	240 min.	103 min.
1	-	-
2	+0.06 mg	+0.02 mg
3	0.04	0.04
4	0.02	+0.04
5	+0.08	0.04
6	0.12	0.16
7	0.08	0.10
8	0.12	0.10
average	0.04 mg	

All weight changes are negative unless otherwise noted.

Average weight change of Andersen substrates after sampling filtered effluent from a hot side precipitator on a coal fired boiler.

Temperature = 635°F Sampling Time = 90 min. Average = 0.02 mg

TABLE A-14

TYPICAL AVERAGE AMOUNTS OF COLLECTION FOR AN ANDERSEN IMPACTOR

Stage	Site and Amount in mg						
	A	B	C	D	E	F	G
1	1.13	0.37	1.70	15.79	0.59	6.74	9.70
2	0.78	0.27	1.29	6.94	0.39	2.45	6.97
3	0.84	0.30	1.08	11.62	0.35	2.08	8.23
4	0.80	0.28	1.17	7.23	0.34	1.63	8.93
5	0.95	0.32	2.12	8.73	0.25	2.52	12.62
6	1.25	0.29	4.96	5.56	0.48	5.30	14.48
7	1.84	1.10	5.06	2.99	1.08	4.99	8.61
8	2.72	1.68	2.64	0.66	1.00	2.52	4.39
F	22.40	4.51	5.53	3.85	3.91	3.01	8.56
Sampling Time (min).	431	921	210	38	371	140	255
Stack Temp. (°C)	121	41	335	166	66	152	167

A. Wet scrubber at submerged arc ferro-alloy furnace.
B. Wet precipitator on aluminum reduction pot lines.
C. Hot side precipitator on coal fired boiler.
D. Precipitator on coal fired boiler.
E. Wet scrubber on open hearth furnace.
F. Pilot scale precipitator on coal fired boiler.
G. Precipitator on coal fired boiler.

Chemware filter membranes made of Zitex, which is a fibrous, porous form of pure TFE-Teflon/Halon. They are produced by Chemplast, Incorporated. A 75-mm, extra fine filter was used. It was desiccated without being wrapped with anything and weighed at various intervals. Then, it was baked for 6 hrs at 205°C and weighed again, desiccated for 24 hrs, and weighed one final time. The baking appeared to cause no damage to the filter. Results are given in Table A-15.

CONCLUSIONS

Several conclusions can be drawn from this study of Andersen filter substrates:

1. From Table A-1 it can be seen that the Cahn Model G-2 Electrobalance used in this study as well as our normal laboratory and field test work is quite stable in day-to-day operation. Repetitive weighings of metal objects agreed within 0.02 mg over a six day period. This degree of uncertainty represents a very small percentage of normal stage weights (e.g., Table A-14).

2. Tables A-2 and A-3 indicate that the substrates lose about .10-.20 mg of absorbed moisture when desiccated for 24 hours at room temperature. Although further desiccation does not remove additional moisture, losses do occur when clean air is pulled through the impactors. These losses are approximately .05-.10 mg for six hours testing at 0.5 acfm at room temperature (24°C), and .10-.20 mg at elevated temperatures (120°C). These results are summarized in Tables A-9, A-10, A-11 and A-12. Although a definitive reason for this has not been

TABLE A-15

CUMULATIVE WEIGHT CHANGE OF TEFLON FILTER SUBSTRATE AFTER DESICCATION AND BAKING

Original weight - 509.08 mg

Hours of Desiccation	
24	-0.04 mg
48	-0.04
72	-0.04
96	-0.02
After baking 6 hrs at 205 °C	-0.26
After 24 hrs desiccation	-0.22

established, one possibility is that the moving air dries the substrates more than normal desiccation. This explanation is consistent with the larger losses which occur when clean, hot air is drawn through the impactors.

3. Table A-4 confirms the reabsorption of water vapor by previously desiccated substrates upon exposure to a humid atmosphere. Within ½ hour, the weight lost during a desiccation period of 24 hours is regained (∿.10-.20 mg). For this reason, the substrates and stage catches from impactor tests should be desiccated for at least 24 hours before weighing, and the weighing should be done immediately upon removing each substrate from the desiccator.

4. Tables A-5, A-6, A-7 and A-8 indicate that if careful attention is maintained in weighing, loading, and unloading substrates, then the handling losses are not significantly better if the substrates are "cleaned" before use. Poor handling and impactor cleaning techniques would, of course, tend to magnify these errors.

5. The field test data shown in Tables A-13 and A-14 indicate that weight losses which may occur during impactor measurements can amount to more than 50% of the particulate catch for any given stage, but more often are less than 20%. The errors are most significant when sampling sources with extremely low grain loadings under circumstances that do not permit extended sampling times.

6. The data tabulated in Table A-15 shows that the weight losses as indicated in Tables A-9 and A-10 can be either significant or insignificant depending on the amount of particulate collected per stage. Partial compensation for this weight loss could be obtained by adding approximately 0.1 mg per stage.

7. Although the weight losses were progressively higher for impactor loading and unloading, sampling clean cool air, and sampling clean warm air respectively, it was not proven whether the losses were due to drying, to loss of filter material, or both. One can generalize all the results, including field tests, as indicating that with prebaking, 24 hour desiccation, careful weighing and loading, careful unloading and impactor cleaning, post test desiccation for 24 hours, and careful final weighing, the weight losses can be minimized, and will probably be less than .20 mg per stage. This may or may not seriously degrade the accuracy of the particle size measurements, depending upon the amount of material collected. It would be desirable to collect 2-3 mg of material on every substrate, but this could result in excessively long sampling times at some locations, or overloading of other stages for some particle size distributions.

APPENDIX B

GLASS FIBER SUBSTRATE WEIGHT GAINS

Glass fiber filter media when exposed to stack-type environments are subject to possible gas phase reactions with the flue gases. In inertial impactors using glass fiber material as substrates, the most important result of the reactions is the possible weight changes which may occur in the substrates. Ideally, the only weight change in a substrate should be the weight change caused by the collection of particulate matter from the flue gas, but field test results have shown that glass fiber is not the "ideal" substrate, even though it may be a satisfactory one, if the gas phase reaction weight change problem can be brought under control.

With this problem in mind, tests were designed to gain an understanding of the weight changes and to facilitate the selection of a sufficiently inert filter material for impactor substrates. A suitable substrate material would be one which has stable weight characteristics and is mechanically strong to resist cutting, tearing, and loss of material.

Several types of filter material were obtained from commercial suppliers for testing: Gelman Types A, AE, and SpectroGrade glass fiber filter material, Mine Safety Appliance 1106-BH glass fiber filter material; Reeve-Angel 900 AF and 934 AH glass fiber material; Whatman GF/A and GF/D glass fiber material; Chemplast teflon filter membranes; and Pallflex Tissuquartz 2500 QAD (See Table B-I). The method chosen to test the filter media was to expose them directly to the flue gases for time intervals characteristic of an impactor run. Several Gelman stainless steel 47 mm filter

TABLE B-1

FILTER TYPES

Gelman Type A	GA
Gelman Type AE	GAE
Gelman SpectroGrade	SA
Mine Safety Appliance 1106 BH	MSA 1106 BH
Reeve-Angel 900 AF	RA 900 AF
Reeve-Angel 934 AH	RA 934 AH
Whatman GF/A	GF/A
Whatman GF/D	GF/D
Chemplast Teflon Filter	Teflon
Pallflex Tissuquartz 2500 QAD	Quartz

holders were used to accomplish this. These holders were assembled as a series filter arrangement and run just as an Andersen Stack Sampler would be run. The first filter holder was a pre-filter which removed the particulate. The remainder of the filters, each in its holder, were exposed only to the flue gas.

Before the weighed filter samples were loaded in the Gelman holders, they were cut to 47 mm size where necessary, baked in a laboratory oven at 287°C (550°F) for two to three hours, and desiccated for at least twenty-four hours. The samples remained in the desiccator until just prior to use.

Two sampling sites were chosen for testing of the filter media. Both sources were places where previous impactor runs had been made, and the sources were different types. The first testing was done at the outlet of a hotside ESP at Citadel Cement Company between February 12th and February 21st, 1975. Two gas fired kilns were in operation while the tests were being performed. Outlet temperatures were in the neighborhood of 260°C (500°F). Other data, including flowrates and weight gains, are listed in Table B-2. Filter 1a includes the particulate catch in each case.

The second site was Bull Run Power Plant. The tests were performed at the coal fired boiler precipitator outlet during two periods. The first period was February 25 to February 28, 1975. Flue gas temperatures ranged from 130°C (265°F) to 180°C (355°F). Other data are listed in Table B-3. The second testing at Bull Run Power Plant was April 1 to April 3, 1975, with flue temperatures varying from 138°C (280°F) to 174°C (345°F). Table B-4 contains this data.

In the test at Citadel and the first test at Bull Run, there was a problem with the filter material sticking to the o-ring and the support screen of the holder. This created a nuisance and also added

TABLE B-2

CITADEL CEMENT

		CC-1			CC-2			CC-3			CC-4		
	Date		2-12-75			2-18-75			2-19-75			2-21-75	
("Hg)	Amb. Pres.		29.7			29.5			29.7			29.9	
(°F)	Amb. Temp.		62			68			48			58	
(°F)	Stack Temp.		510			480			480			505	
(ft^3)	Gas Vol.		12.287			23.808			24.030			33.068	
(°F)	Avg. Gas Meter Temp.		58			74			53			79	
(min)	Run Time Ori. ID		60 3348-.059			120 3348-.059			120 3348-.059			240 3348-.059	
(ml)	Cond. H_2O % H_2O		74 (29.6)	22% used for flowrate		121 (26.6)	22.0		131 (27.2)	22.0		97 (28.0)	22.0
(acfm)	Flow Rate: - Ori. - Gas Meter		0.414 0.438	} 0.426		0.383 0.390	} 0.387		0.391 0.410	} 0.400		0.147 0.1535	} 0.150
("Hg)	Avg. Probe ΔP		2.4			3.0			3.0			15.0	
("H_2O)	Ori. ΔP		11.0			10.3			10.4			2.6	
	1a	GA	3.22 mg		GA	10.58 mg		GA	9.48 mg		GA	4.38	
	1b	-	-	Silicone o-rings stuck to filters	GA	0.44		GA	0.84		MSA 1106 BH	2.14	
	2	SA	0.28		SA	0.92	Slight brown ring	MSA 1106 BH	1.42		Teflon	-0.02	
	3	GA	-0.48		RA 900 AF	1.16		RA 900 AF	1.70		GA	0.90	
	4	-	-		MSA 1106 BH	1.02	Slight brown ring	SA	1.66	Stuck to metal support	RA 900 AF	2.40	
	5	-	-		-	-					MSA 1106 BH	1.92	
	6	-	-		-	-					Teflon	0.00	
						Teflon o-rings			Teflon o-rings			Teflon o-rings	

TABLE B-3

BULL RUN STEAM PLANT

		BRSP-1	BRSP-2	BRSP-3	BRSP-4	BRSP-5	BRSP-6	BRSP-7
	Date	2-25-75	2-25-75	2-26-75	2-26-75	2-27-75	2-28-75	2-28-75
("Hg)	Amb. Pres.	29.08	29.08	29.44	29.42	29.36	29.10	29.10
(°F)	Amb. Temp.	54°	61	53	69	64	41	50
(°F)	Stack Temp.	275	265	275	275	300	355	355
(ft³)	Gas Vol.	11.062	18.767	80.928	34.269	140.245	8.433	-
(°F)	Avg. Gas Meter Temp.	81	73	81	82	79	74	-
(min)	Run Time Ori. ID	60 3348-.059	60 3348-.059	240 3348-.059	120 3348-.059	480 3348-.059	30 3348-.059	0 -
(ml)	Cond. H_2O % H_2O	6.0 (3.8) 7.5 used in flow-rate calculations	11.4 (4.9) 7.5	57.5 (5.6) 7.5	23.8 (5.7) 7.5	90.8 (5.7) 7.5	4.8 (4.6) 7.5	- -
(acfm)	Flow Rate: -Ori. -Gas Meter	0.183 0.189 0.186	0.249 0.258 0.254	0.286 0.285 0.286	0.231 0.239 0.235	0.230 0.235 0.232	0.266 0.269 0.268	- -
("Hg)	Avg. Probe ΔP (+ ΔP across orifice)	8.8	12.65	12.6	12.7	13.95	12.5	-
("H_2O)	Ori. ΔP	6.5	14.9	18.5	12.8	12.7	12.9	-
	1a	GA 12.29 mg	GA 26.50	GA -	GA 37.99	GA -	GA 23.41	GA 0.34
	1b	MSA 1106 BH 0.43	GA 0.44	RA 900 AF 0.77	MSA 1106 BH 0.08	GA 3.27 Moderately brown on edge.	MSA 1106 BH 0.69	GA 0.38
	2	GA 0.16	RA 900 AF 0.69	MSA 0.16	RA 900 AF 0.03	MSA 1106 BH 3.65 Moderately brown near o-ring	SA -0.12 Torn	MSA 1106 BH 0.77
	3	RA 900 AF 0.37	MSA 1106 BH -0.14 Stuck to o-ring & support severely	Teflon 0.01	GA 0.24	SA 0.68 Severely cut light brown	GA 0.27	SA -0.10 Torn
	4	Teflon 0.01	Teflon 0.00	SA 0.12	SA 0.18	GA 0.53 No discoloration	SA 0.66	GA 0.38
	5	MSA 1106 BH 0.27	RA 900 AF 0.56	GA -0.04 Severely cut	GA 0.41	Teflon 0.00	Teflon -0.01	MSA 1106 BH 0.70
	6	GA 0.19	GA -0.74 Stuck to o-ring & cut by it.	SA 0.31	Teflon 0.07	MSA 1106 BH 1.00 Slight browning	MSA 1106 BH 0.71	Teflon 0.06
			All filters stuck slightly to support. As much as possible recovered.	This (and all that follow) are Spectro Grade A from batch 8192.				This set not run; placed in stack and taken out immediately.

TABLE B-4

BULL RUN STEAM PLANT

		BRSP-8	BRSP-9	BRSP-10	BRSP-11	BRSP-12	BRSP-13
	Date	4/1/75	4/2/75	4/2/75	4/2/75	4/3/75	4/3/75
("Hg)	Amb. Pres.	29.28	29.15	29.15	29.15	29.12	29.12
(°F)	Amb. Temp.	84	78	92	89	48	57
(°F)	Stack Temp.	315	315	315	315	345	230
(ft^3)	Gas Vol.	52.172	13.004	6.531	6.516	50.284	12.697
(°F)	Avg. Gas Meter Temp.	103	92	107	99	53.5	69
(min.)	Run Time	240	60	30	30	240	60
(ml.)	Cond. H_2O	48.9	11.0	6.0	5.8	48.8	13.3
	% H_2O	(6.6) 7.5 used in flow-rate calculations	(5.2) 7.5	(5.9) 7.5	(5.6) 7.5	(6.1) 7.5	(6.2) 7.5
	Ori. ID	3348 - .059	3348 - .059	3348 - .059	3348- .059	3348 - .059	3348- .059
("H_2O)	Ori. ΔP	9.7	10.3	10.3	10.3	10.3	10.3
("Hg)	Avg. Probe ΔP	7.1	4.35	4.75	4.65	6.6	4.35
(acfm)	Flowrate:						
	- Ori.	0.242	0.267	0.261	0.262	0.272	0.260
	- Gas meter	0.238	0.272	0.262	0.266	0.266	0.265
*	1a	GA -	GA -	GA -	GA -	GA -	GA -
	1b	GA 3.68	GA 1.74	GA 1.00	GA 0.84	GA 2.74	GA 0.12
	2a	GAE 8.54	GAE 1.26	GAE 1.76	GAE 0.96	GAE 6.66	GAE 1.08
	2b	GAE	GAE	GAE	GAE	GAE	GAE
	3a	SA 2.02	SA 0.00	SA 0.08	SA -0.12	SA 4.06	SA 0.10
	3b	SA	SA	SA	SA	SA	SA
	4a	Quartz -0.50	Quartz -1.96	Quartz 0.12	Quartz -1.40	Quartz -5.16	Quartz 0.66
	4b	Quartz	Quartz	Quartz	Quartz	Quartz	Quartz
	5a	GF/A 0.52	GF/A 0.02	GF/A 0.08	GF/D 0.00	GF/D -0.04	GF/D 0.18
	5b	GF/A	GF/A	GF/A	GF/D	GF/D	GF/D
	6a	RA 934 AH 0.46	RA 934 AH 0.02	RA 934 AH 0.24	RA 934 AH 0.04	RA 934 AH 0.08	RA 934 AH 0.32
	6b	RA 934 AH	RA 934 AH	RA 934 AH	RA 934 AH	RA 934 AH	RA 934 AH

NOTE:

GA - Gelman Type A
GAE - Gelman Type AE
SA - Gelman Spectro Glass Fiber, Type A
Quartz - Pallflex Tissuquartz 2500 QAD
GF/A - Whatman GF/A
GF/D - Whatman GF/D
RA 934 AH - Reeve Angel 934 AH

*Combined weight of the two filters per holder, except for holder 1 where the weight of the prefilter (1a) has been eliminated.

the possibility that some material might be overlooked. For the tests in April at Bull Run, teflon gaskets were cut which fitted directly under the o-ring and on the support screen. The filter sample was then between teflon gaskets and the gaskets were preweighed with the filter sample.

Two identical 47 mm filters were run in each holder. Originally, it was hoped that we might be able to obtain weight gain data from each of these but because of a tendency of the filters to adhere to one another the weight gains of both were lumped together. All the results are shown in Table B-4.

The sampling times and flowrates used were supposed to approximate the sampling time and flowrate of a typical Andersen Stack Sampler test. Sampling times varied from thirty minutes to eight hours which met the above requirement. The flowrates used, however, were somewhat below that of the ideal Andersen flowrate of 0.5 cfm. On all of the tests in which the teflon membranes were used, the flowrates were only half as high as the desired flowrate of 0.5 cfm because the pressure drop across the membrane was large. (Even so, the ratio between flowrate and filter surface area at these lower flowrates approximated the same ratio of these for an Andersen Stack Sampler.) No attempt was made at isokinetic sampling since only the flue gas was of interest.

After each run, the filters were desiccated for at least 24 hours and weighed. Any gas phase reaction was then detected by a weight change. A report by Forrest Newman[2] indicates weight gains in glass fiber filters are possible by conversion of SO_2 to various sulfates.

The results of all the tests are listed in the tables. From these results, no definite trend emerged to indicate that the weight gains depended upon flowrate. However, there seems to be a relation between weight gain and total exposure time of the filter to the flue gas, regardless of the flowrate. Also, temperature may be an important factor in the weight gains. At Citadel Cement Company where the temperature was almost double that of Bull Run Power Plant, the weight gains were much higher than the Bull Run series. Since the two sources are different types, this comparison may not be valid, but BRSP-6, a thirty-minute run at 180°C (355°F), showed gains which exceeded those of BRSP-3, a four hour run at 135°C (275°F).

Both Whatman types, GF/A and GF/D, and the Reeve Angel 934 AH showed little tendency for weight gain, and seem to be candidates for future use as impactor substrates. The Pallflex quartz showed loss of weight, but it was very fragile and tended to break and tear easily, which may have resulted in a loss of some of the filter material.

Chemical analyses were performed on all the filter materials that had been tested in the Gelman holders. This includes the tests at Citadel Cement and those at Bull Run Steam Plant. Soluble sulfate determination and pH tests were run on each sample, except the teflon samples which had shown very little weight change. These results are shown in Tables B-5, B-6, B-7.

The data in these tables indicate that sulfate is responsible for the majority of the observed weight gain on each filter. (Some filters which had small weight gains appeared to have picked up little sulfate, but this may only reflect the limits of our experimental accuracy.) In each case, the pH of the sample was more acidic after it had been run, indicating possible sulfate gain.

The work of Charles Gelman and J. C. Marshall of the Gelman Instrument Company, makers of various filter media and equipment, seems to confirm that SO_2 absorption is the cause of the weight gains.

TABLE B-5

FILTER BLANKS (UNTREATED)

Type	mg $SO_4^=$	pH
GA	0.04	8.[illegible]
MSA	0.18	9.[illegible]
RA 900 AF	0.06	9.8
SA	Negligible	5.6
Quartz	Negligible	6.6
GAE	Negligible	9.2
RA 934 AH	0.06	7.2
GF/A	Negligible	8.1
GF/D	Negligible	7.0

TABLE B-6

CITADEL CEMENT

	CC-1					CC-2					CC-3				
		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed*		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed
1a	GA	3.22	2.1	7.1	½	GA	10.58	5.02	8.1	½	GA	9.48	4.83	7.7	½
1b	-	-	-	-	-	GA	0.44	0.10	8.0	Whole	GA	0.84	0.27	7.2	½
2	SA	0.28	0.44	8.1	Whole	SA	0.92 Slight brown ring	0.94	8.1	½	MSA 1106 BH	1.42	0.90	7.7	½
3	GA	-0.48	-		-	RA 900 AF	1.16	0.83	7.7	½	RA 900 AF	1.70	1.45	8.1	½
4	-	-	-	-	-	MSA 1106 BH	1.02 Slight brown ring	0.76	7.7	½	SA	1.66 Stuck to metal support	1.85	8.7	½
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
			Silicone o-rings stuck to filters				Teflon o-rings					Teflon o-rings			

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*On those filters containing relatively large amounts of particulate, only a portion of the filter was analyzed. Sulfate was calculated on a whole filter basis.

TABLE B-6
(CONTINUED)

CC-4

	Mg. Wt. Gain	Mg. $SO_4^{=}$	pH	Filter Portion Analyzed
GA	4.38	2.0	7.4	¼
MSA 1106 BH	2.14	1.67	6.9	¼
Teflon	-0.02	-	-	-
GA	0.90	0.30	7.1	½
RA 900 AF	2.40	2.27	7.0	¼
MSA 1106 BH	1.92	1.52	7.5	¼
Teflon	0.00 Teflon o-rings	-	-	-

TABLE B-7

BULL RUN

	BRSP-1					BRSP-2				
		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed
1a	GA	12.29	0.56	5.6	¼	GA	26.50	0.91	5.4	¼
1b	MSA 1106 BH	0.43	0.17	5.7	Whole	GA	0.44	0.04	5.9	Whole
2	GA	0.16	0.06	5.5	Whole	RA 900 AF	0.69	0.20	6.9	Whole
3	RA 900 AF	0.37	0.26	5.6	Whole	MSA 1106 BH	-0.14	Stuck to o-ring and support	-- -	
4	Teflon	0.01				Teflon	0.00			
5	MSA 1106 BH	0.27	0.11	6.7	Whole	RA 900 AF	0.56	0.26	7.7	Whole
6	GA	0.19	0.04	6.4	Whole	GA	-0.74	Stuck	-	
						All filters stuck at least slightly				

*Same note as Citadel

TABLE B-7
(CONTINUED)

	BRSP-3					BRSP-4				
		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed
1a	GA	-	-	-		GA	37.99	-	4.4	¼
1b	RA 900 AF	0.77	0.22	4.2	Whole	MSA	0.88	0.26	5.5	Whole
2	MSA	0.16	0.11	4.5	Whole	RA 900 AF	0.83	0.25	5.7	Whole
3	Teflon	0.01	0.00	5.8	Whole	GA	0.24	0.06	5.1	Whole
4	SA	0.12	0.23	4.8	Whole	SA	0.18	0.29	5.3	Whole
5	GA	-0.04	Severely cut	-	-	GA	0.41	0.03	5.1	3/4
6	SA	0.31	0.05	4.8	Whole	Teflon	0.07			

TABLE B-7
(CONTINUED)

		BRSP-5					BRSP-6				
		Mg. Wt. Gain	Mg. $SO_4^=$		pH	Filter Portion Analyzed		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed
1a	GA	-	-		-	-	GA	23.41	1.28	3.9	¼
1b	GA	3.27	1.95	Moderately brown on edge	3.0	½	MSA 1106 BH	0.69	0.24	6.4	Whole
2	MSA 1106 BH	3.65	2.34	Moderately brown near o-ring	3.0	½	SA	-0.12	Torn	-	-
3	SA	0.68	1.40	Severely cut	3.0	Whole	GA	0.27	0.02	6.5	Whole
4	GA	0.53	0.103		5.6	Whole	SA	0.66	0.10	5.7	Whole
5	Teflon	0.00	-		-	-	Teflon	-0.01	-	-	-
6	MSA 1106 BH	1.00	0.52	Slight brown ring	5.8	½	MSA 1106 BH	0.71	0.28	6.4	Whole

TABLE B-7
(CONTINUED)

BRSP-7

		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed
1a	GA	0.34	0.12	6.8	Whole
1b	GA	0.38	0.12	6.9	Whole
2	MSA 1106 BH	0.77	0.37	7.8	Whole
3	SA	-0.10	Torn	-	-
4	GA	0.38	0.08	7.2	Whole
5	MSA 1106 BH	0.70	0.31	7.8	Whole
6	Teflon	0.06	-	-	-

This set not run; placed in stack, heated for 30 minutes, and taken out.

BRSP-8

		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed
1b	GA	3.68	1.62	3.4	½
2a & b	GAE	8.54	5.16	3.3	¼ each filter
3a & b	GSA	2.02	1.54	3.5	½ each filter
4a & b	Quartz	-0.50	Negligible	3.6	½ each filter
5a & b	GF/A	0.52	Negligible	5.9	2 wnole filters
5a & b	GF/D	-	-	-	-
6a & b	RA 934	0.24	Negligible	5.6	2 whole filters

TABLE B-7
(CONTINUED)

	BRSP-9					LRSP-10				
		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed
1b	GA	1.74	0.92	3.4	½	GA	1.00	0.42	3.7	Whole
2a & b	GAE	1.26	0.46	5.8	½ each filter	GAE	1.76	0.29	7.2	½ each filter
3a & b	GSA	0.00	0.05	5.3	2 whole filters	CSA	0.08	0.04	5.9	2 whole filters
4a & b	Quartz	-1.96	-	-	-	Quartz	0.12	Negligible	3.5	2 whole filters
5a & b	GF/A	0.02	Negligible	6.6	2 whole filters	GF/A	0.08	-	-	-
5a & b	GF/D	-	-	-	-	GF/D	-	-	-	-
6a & b	RA 934 AH	0.02	Negligible	6.1	2 whole filters	RA 934 AH	0.24	Negligible	6.3	2 whole filters

TABLE B-7
(CONTINUED)

	BRSP-11					BRSP-12				
		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed
1b	GA	0.84	0.37	4.1	Whole	GA	2.74	1.48	2.8	Whole
2a & b	GAE	0.96	0.44	7.8	2 whole filters	GAE	6.66	4.82	2.7	½ each filter
3a & b	GSA	-0.12	0.04	5.8	2 whole filters	GSA	4.06	4.99	2.7	½ each filter
4a & b	Quartz	-1.40	-	-	-	Quartz	-5.16	-	-	-
5a & b	GF/A	-	-	-	-	GF/A	-	-	-	-
5a & b	GF/D	0.00	0.05	6.6	2 whole filters	GF/D	-0.04	0.13	5.9	2 whole filters
6a & b	RA 934 AH	0.04	0.02	5.9	2 whole filters	RA 934 AH	0.08	0.14	5.6	2 whole filters

TABLE B-7
(CONTINUED)

BRSP-13

		Mg. Wt. Gain	Mg. $SO_4^=$	pH	Filter Portion Analyzed
1b	GA	0.12	0.03	6.0	Whole
2a & b	GAE	1.08	0.32	5.8	2 whole filters
3a & b	GSA	0.10	0.05	5.7	2 whole filters
4a & b	Quartz	0.66	Negligible	3.3	2 whole filters
5a & b	GF/A	-	-	-	-
5a & b	GF/D	0.18	0.06	6.4	2 whole filters
6a & b	RA 934 AH	0.32	0.05	5.5	2 whole filters

They acknowledge that a high pH glass fiber can absorb sulfur dioxide and thus cause erroneous, high, particulate weights. Pate and Lodge's work using Na_2CO_3 treated glass filters as "dosimeters" for SO_2 exposure chambers, with weight gain of the filters being a time function of exposure to SO_2, was mentioned.

According to this article, the SO_2 reaction on glass fiber could cause "a 30% error in the measurement of total suspended particulate matter" in an urban SO_2 atmosphere. The new automotive catalytic mufflers could increase this error. It is possible that flue gases would give even higher errors, especially if the gases have a high moisture content, because the reactivity of SO_2 appears to increase at higher humidity.

Both quartz and glass fiber filter material were tested by Gelman. The quartz was found to be non-reactive to SO_2. The glass fiber materials, Type II and SpectroGrade, prepared with H_2SO_4, were low in SO_2 pickup. The SpectroGrade glass, prepared with HCl, picked up significant amounts of SO_2 (See Table B-8). Their explanation is that the glass prepared with H_2SO_4 has reacted to form $CaSO_4$ to prevent further reaction with SO_2 to form sulfate. (The test used for SO_2 reactivity was to expose the filters to a water saturated atmosphere of SO_2 for 20 hours. Weight change of the filter was measured.)

Another type of SpectroGrade coated with an organic silicone resin showed low SO_2 pickup. This type of SpectroGrade with the silicone treatment is now the standard type.

Use of the siliconized SpectroGrade at elevated temperatures may result in the disappearance of the coating and SO_2 absorption by the filter media since the filter is prepared with HCl.

TABLE B-8

SULFUR DIOXIDE PICKUP

mg/Sheet - 20 Hour Exposure

	mg	pH
SpectroGrade-HCl Siliconized	3	7.1
SpectroGrade HCl	17	9.4
SpectroGrade H_2SO_4	3	6.8
Type II Fiber H_2SO_4	3	6.8
Quartz	0	7.0
Quartz Alkali Strengthened	23 (est.)	9.5

APPENDIX C

CYCLONE DESIGN AND CALIBRATION

This appendix provides engineering data and calibration curves that will be of assistance in the design of cyclone sampling systems. Each of the cyclones listed below have been calibrated and field tested except the SRI-2 and T3A cyclones.

These calibration data were obtained using aerosols generated with a Vibrating Orifice Aerosol Generator. The particles were ammonium fluorescein having a density of 1.35 gm/cc. For particles of different mass densities, the particle size axis, in the accompanying figures, should be shifted according to the relationship

$$D(\rho_2) = D(\rho_1)\sqrt{\frac{\rho_1}{\rho_2}} \quad ,$$

where ρ_1 = the density of the calibration aerosol (1.35 gm/cc),

ρ_2 = the density of the test aerosol (gm/cc),

$D(\rho_1)$ = any point on the particle size axis of the calibration curve, and

$D(\rho_2)$ = the corresponding point on the new graph.

Additional calibration data for cyclones T1B, T2A, and T3A can be found in Chang's paper.[3]

A. CYCLONE SRI-1

Cyclone SRI-1 was designed for a nominal D_{50} of 1 μm at 1 acfm and was derived by extrapolation using the previously calibrated SRI-5 and T2A cyclones which have cut points of approximately 0.5 μm and 2.6 μm at 1.0 acfm, respectively. The calibration curve for SRI-1 is illustrated in Figure C-1. Shop drawings for SRI-1 are provided in Figure C-2.

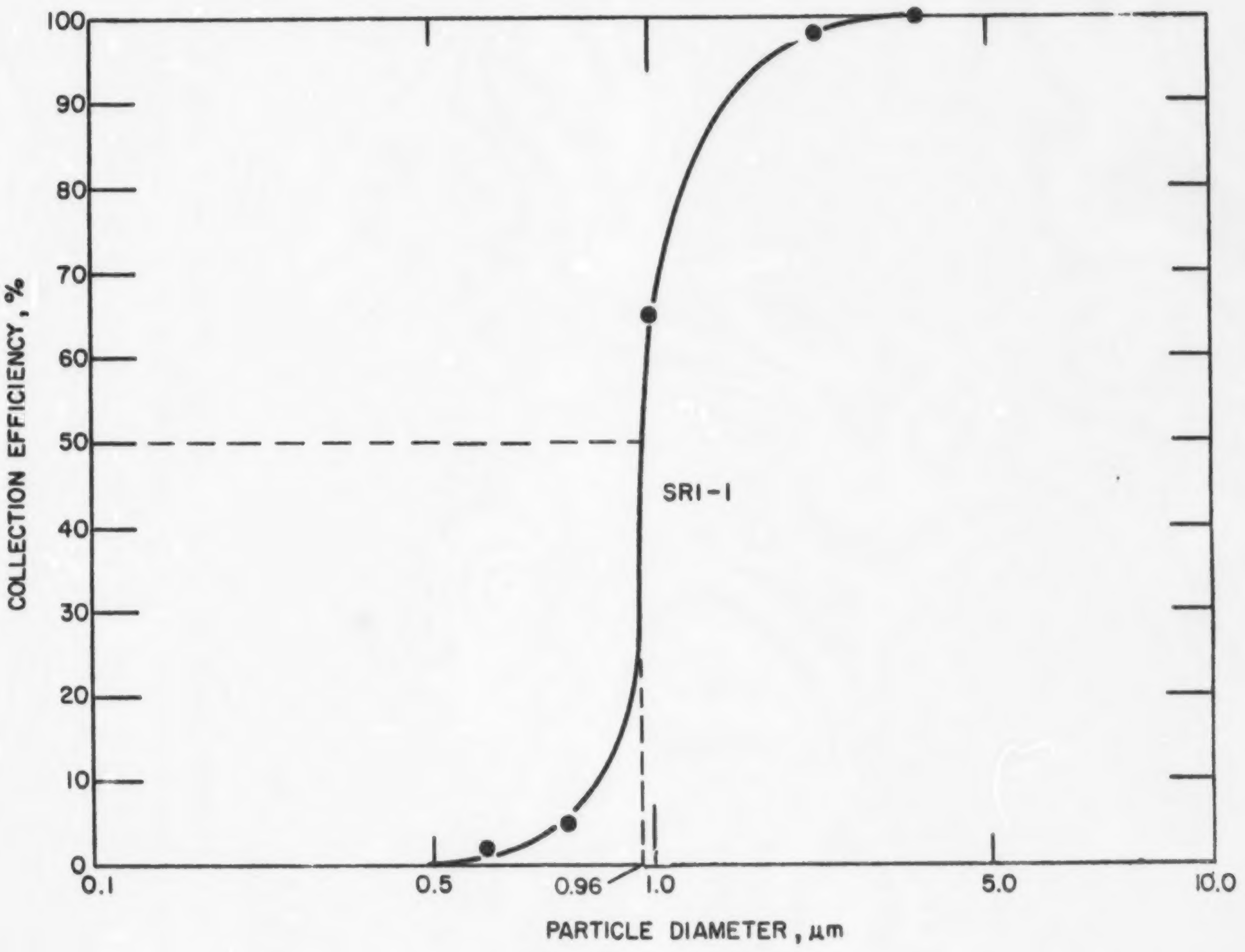
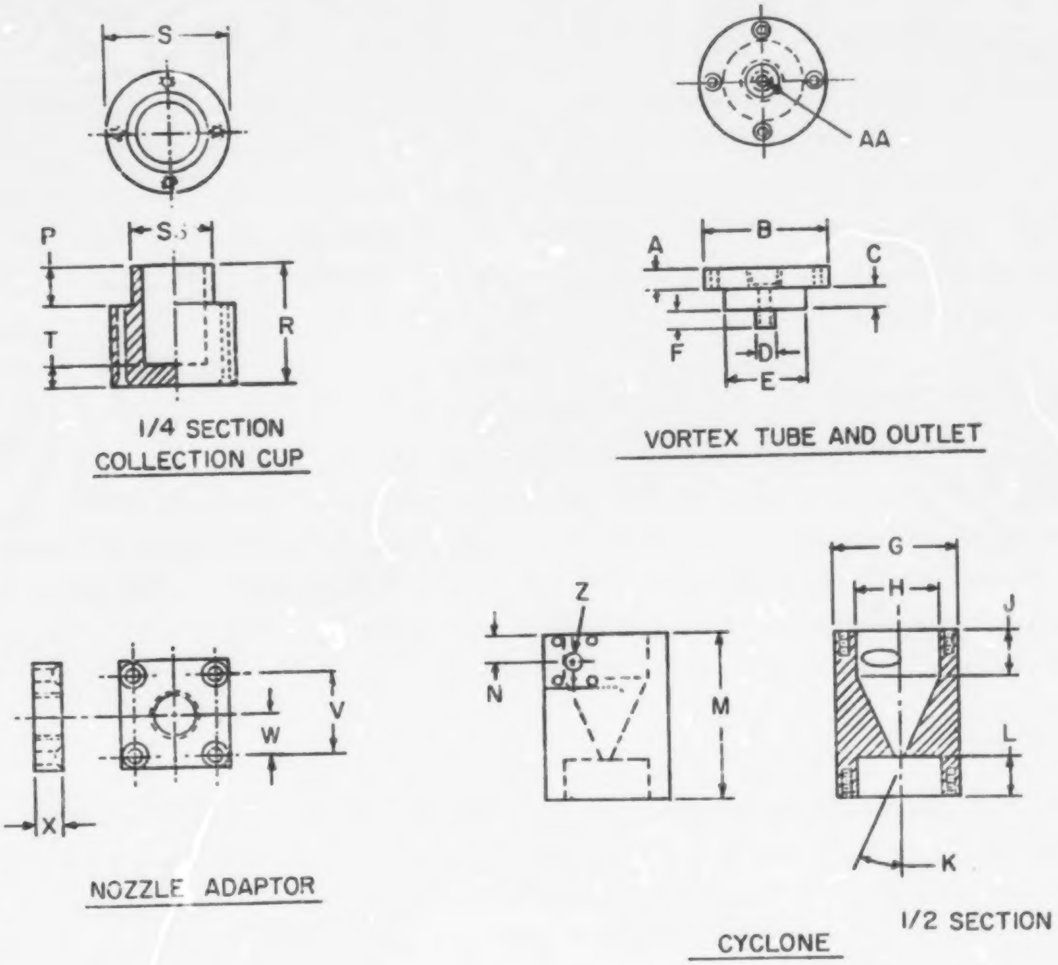


Figure C-1. Collection efficiency versus particle diameter for the SRI-1 cyclone. (22^{o}C, 29.60"Hg, 1.35 gm/cc, 1.0 acfm)



A	0.5	N	0.40
B	1.75	P	1.00
C	0.25	R	1.50
D	0.40	S	1.75
E	1.223	T	0.25
F	0.425	V	0.80
G	1.750	W	0.30
H	1.223	X	0.25
J	0.80	Z	0.295
K	18°30'	AA	0.328
L	1.00	SS	1.25
M	3.183		

Figure C-2. Engineering dimensions (inches) for Cyclone SRI-1.

B. CYCLONE SRI-2

Cyclone SRI-2 was designed using Lapple's equation to achieve a D_{50} of 10 μm at a flowrate of 5 acfm. This was designed especially for use with the Aerotherm High Volume sampling system to obtain size segregated samples for chemical analysis. No calibration data are available at this time. Figure C-3 provides drawings for cyclone SRI-2.

C. CYCLONE SRI-3

This cyclone design was also based on Lapple's equation and was originally intended for use with a point to plane resistivity probe. It has most recently been used as an externally mounted pre-collector cyclone for a Brink Cascade impactor. Figure C-4 illustrates the calibration curve for this cyclone while Figure C-5 provides the shop drawings.

D. CYCLONE SRI-4

This cyclone was designed for use as an inline pre-collector cyclone for the Brink Cascade impactor. The design was modelled after Chang's[3] T1B cyclone. A calibration curve for cyclone SRI-4 is illustrated in Figure C-6. The design drawing is shown in Figure C-7.

E. CYCLONE SRI-5

Cyclone SRI-5 was originally designed as an externally mounted pre-collector cyclone for the Brink Cascade impactor. In a more recent application this design has been used for the third stage of the SRI 3-stage cyclone. As in the case of cyclone SRI-4, this cyclone design was modelled after Chang's[3] T1B cyclone. Figure C-8 illustrates the calibration curve for cyclone SRI-5, while the shop drawing is shown in Figure C-9.

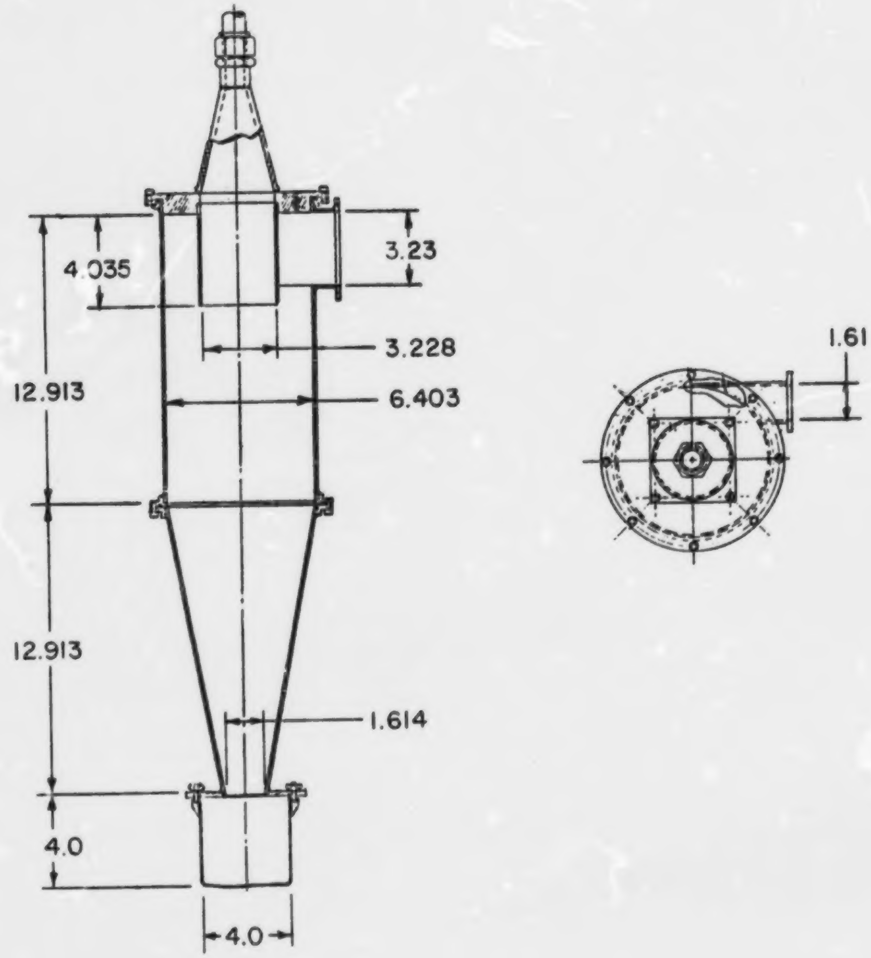


Figure C-3. Engineering dimensions (inches) for Cyclone SRI-2.

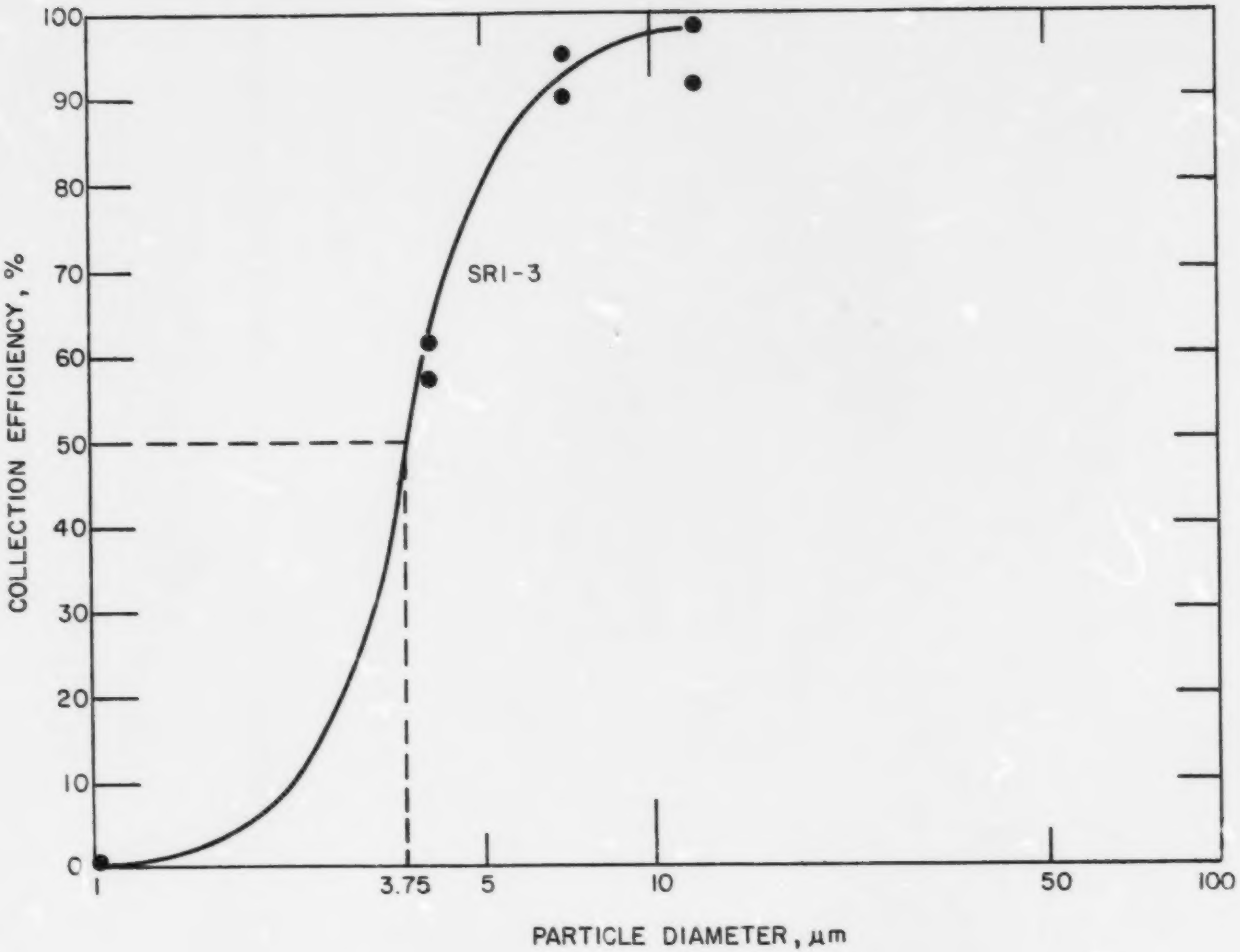


Figure C-4. Collection efficiency versus particle diameter for the SRI-3 cyclone. (22°C, 29.60"Hg, 1.35 gm/cc, 1.0 acfm)

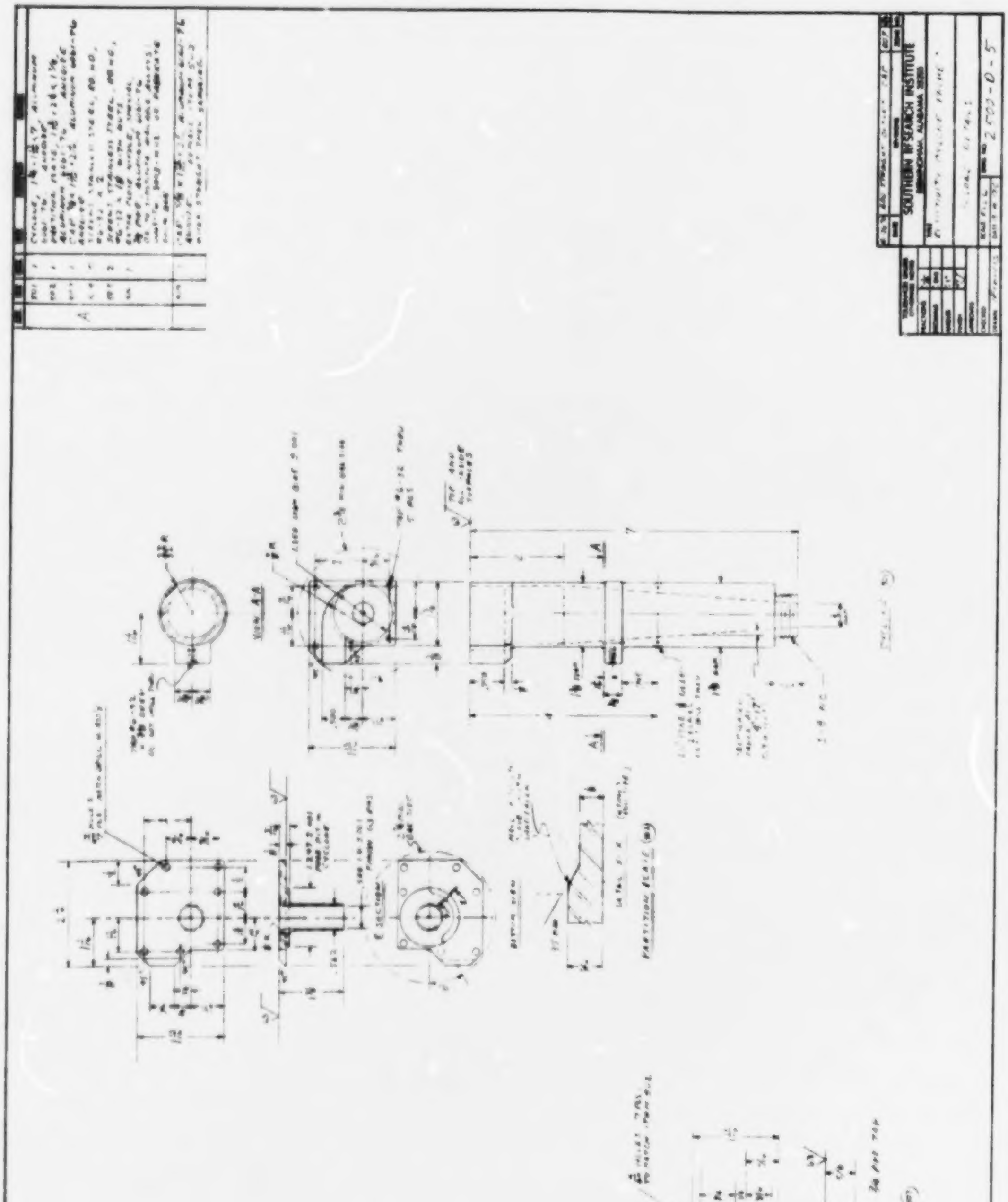
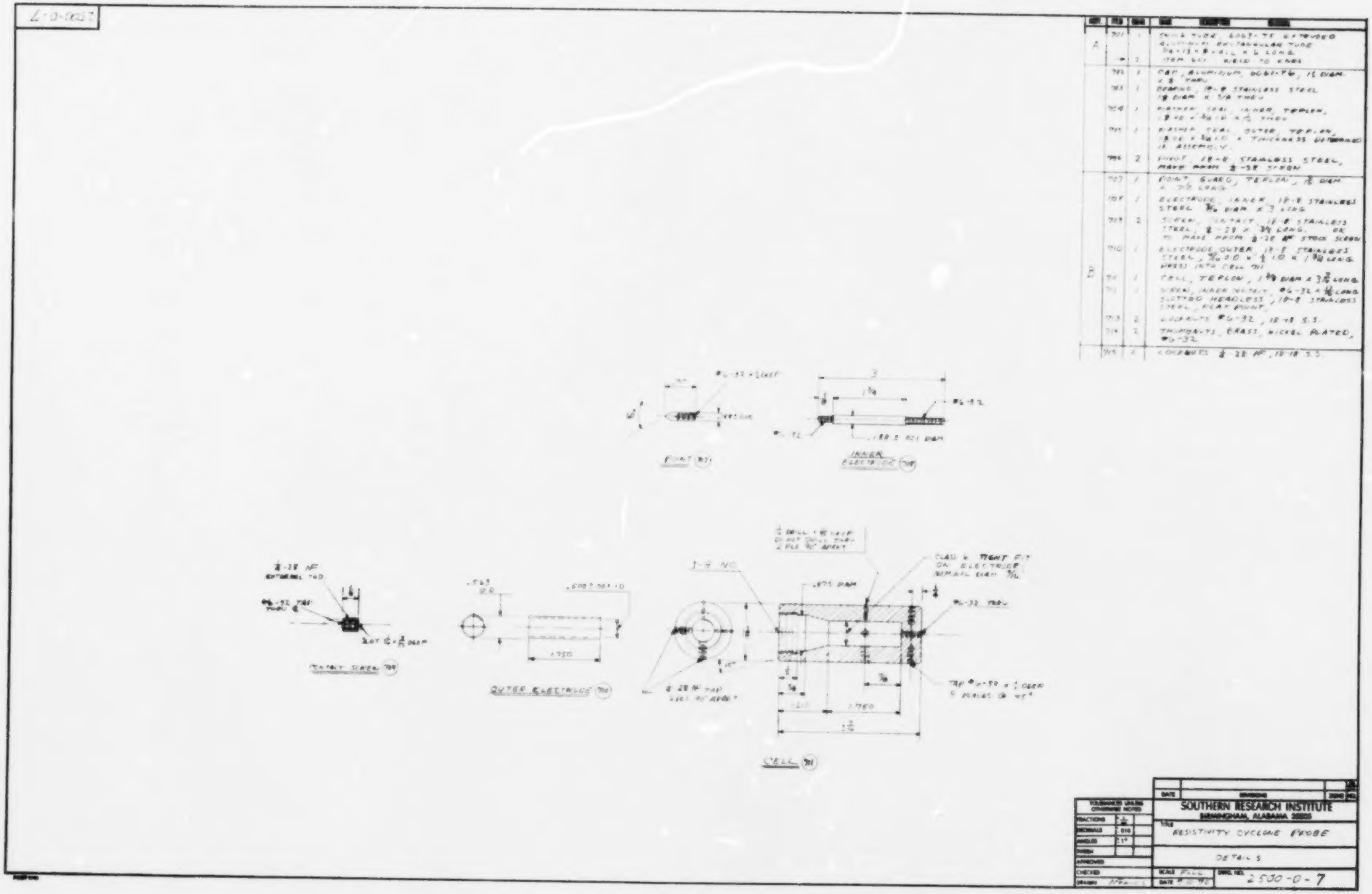


Figure C-5. Engineering dimensions (inches) for Cyclone SRI-3.



2500-0-7
A
B
CAP, ALUMINUM, 6061-T6
BEARING, 18-8 STAINLESS STEEL
WASHER, SEAL, INNER, TEFLON
WASHER, SEAL, OUTER, TEFLON
PIVOT, 18-8 STAINLESS STEEL
POINT, GUARD, TEFLON
ELECTRODE, INNER, 18-8 STAINLESS STEEL
SCREW, CONTACT, 18-8 STAINLESS STEEL
ELECTRODE, OUTER, 18-8 STAINLESS STEEL
CELL, TEFLON
SCREW, INNER CONTACT, #6-32, SLOTTED HEADLESS, 18-8 STAINLESS STEEL, FLAT POINT
LOCKNUTS #6-32, 18-8 S.S.
THUMBNUTS, BRASS, NICKEL PLATED, #6-32
LOCKNUTS
POINT 707
INNER ELECTRODE 708
CONTACT SCREW 709
OUTER ELECTRODE 710
CELL 711
#6-32
3
1.750
SOUTHERN RESEARCH INSTITUTE
BIRMINGHAM, ALABAMA
RESISTIVITY CYCLONE PROBE
DETAILS
SCALE FULL
2500-0-7

Figure C-5A. Engineering dimensions (inches) for Cyclone SRI-3.

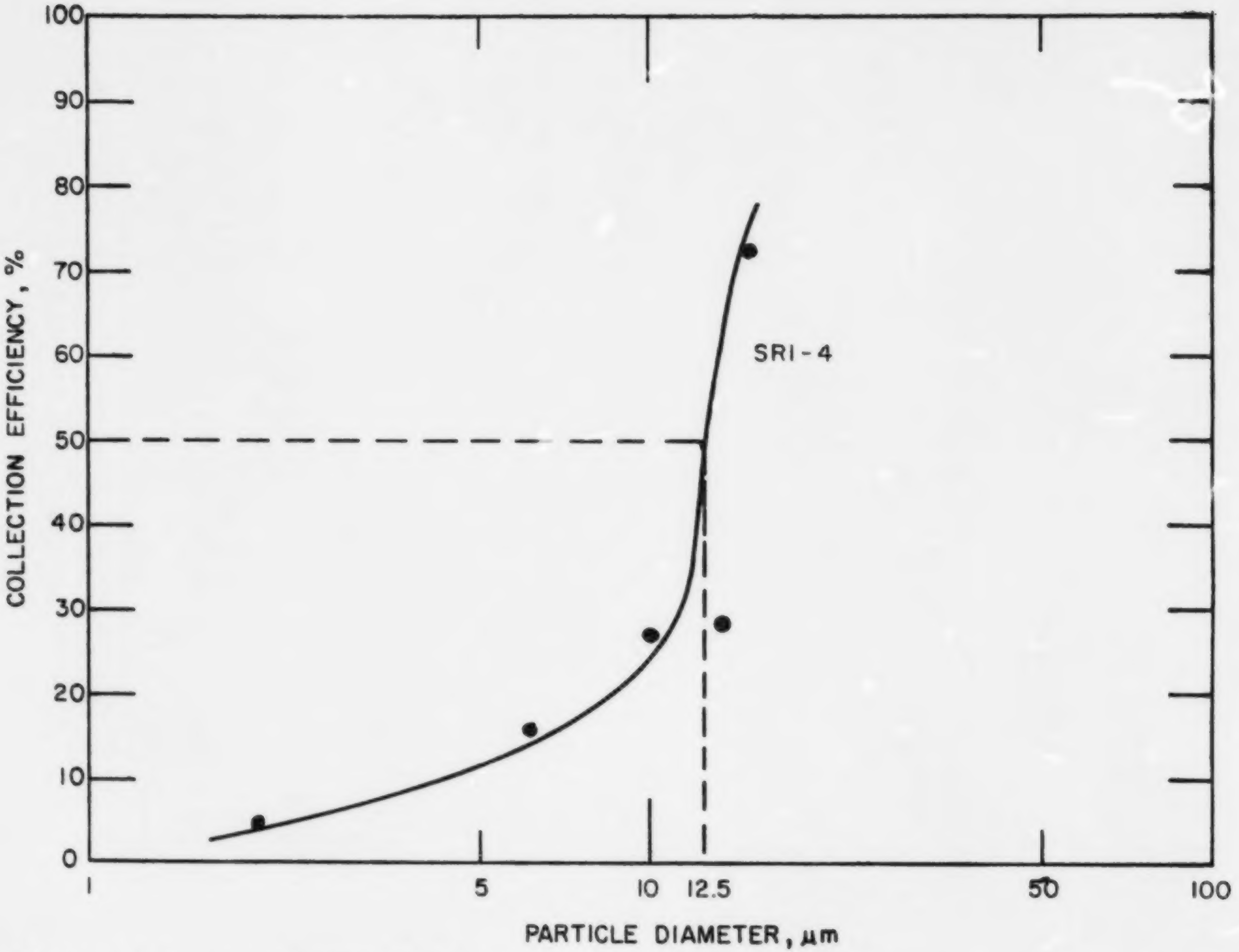
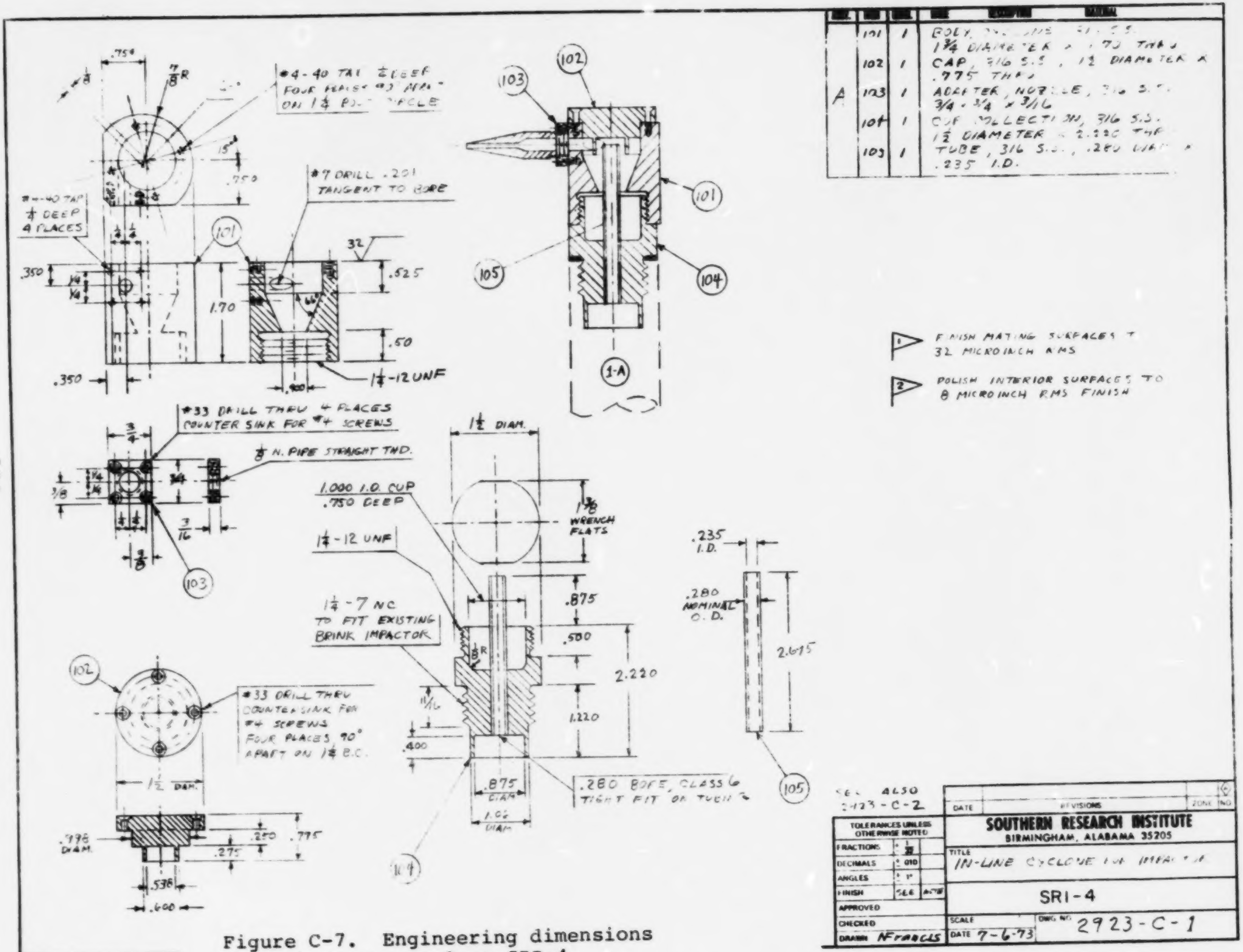


Figure C-6. Collection efficiency versus particle diameter for the SRI-4 cyclone. (22°C, 29.60 "Hg, 1.35 gm/cc, 0.03 acfm)



101
1
BODY, ... 316 S.S.
1¾ DIAMETER x 1.70 THRU
102
1
CAP, 316 S.S., 1½ DIAMETER x .775 THRU
A
103
1
ADAPTER, NOZZLE, 316 S.S.
¾ x ¾ x 3/16
104
1
CUP COLLECTION, 316 S.S.
1½ DIAMETER x 2.220 THR
105
1
TUBE, 316 S.S., .280 DIA x .235 I.D.
FINISH MATING SURFACES TO 32 MICROINCH RMS
POLISH INTERIOR SURFACES TO 8 MICROINCH RMS FINISH
#4-40 TAP ¼ DEEP FOUR PLACES 90° APART ON 1¼ DIA. CIRCLE
#4-40 TAP ¼ DEEP 4 PLACES
#7 DRILL .201 TANGENT TO BORE
7/8 R
.750
.350
1.70
.525
.50
1¼-12 UNF
32
#33 DRILL THRU 4 PLACES COUNTER SINK FOR #4 SCREWS
⅛ N. PIPE STRAIGHT THD.
3/16
1.000 I.D. CUP .750 DEEP
1¼-12 UNF
1¼-7 NC TO FIT EXISTING BRINK IMPACTOR
1½ DIAM.
1⅜ WRENCH FLATS
.875
.500
2.220
1.220
.400
11/16
.875 DIAM
1.06 DIAM
.280 BORE, CLASS 6 TIGHT FIT ON TUBING
.235 I.D.
.280 NOMINAL O.D.
2.675
#33 DRILL THRU COUNTERSINK FOR #4 SCREWS FOUR PLACES 90° APART ON 1¼ B.C.
1½ DIAM.
.998 DIAM.
.250
.275
.775
.536
.600
1-A
SEE ALSO 2923-C-2
DATE
REVISIONS
ZONE
NO
SOUTHERN RESEARCH INSTITUTE
BIRMINGHAM, ALABAMA 35205
TOLERANCES UNLESS OTHERWISE NOTED
FRACTIONS ± 1/32
DECIMALS ± .010
ANGLES ± 1°
FINISH SEE ...
APPROVED
CHECKED
DRAWN N FRANCIS
TITLE IN-LINE CYCLONE FOR IMPACTOR
SRI-4
SCALE
DATE 7-6-73
DWG. NO. 2923-C-1

Figure C-7. Engineering dimensions (inches) for Cyclone SRI-4.

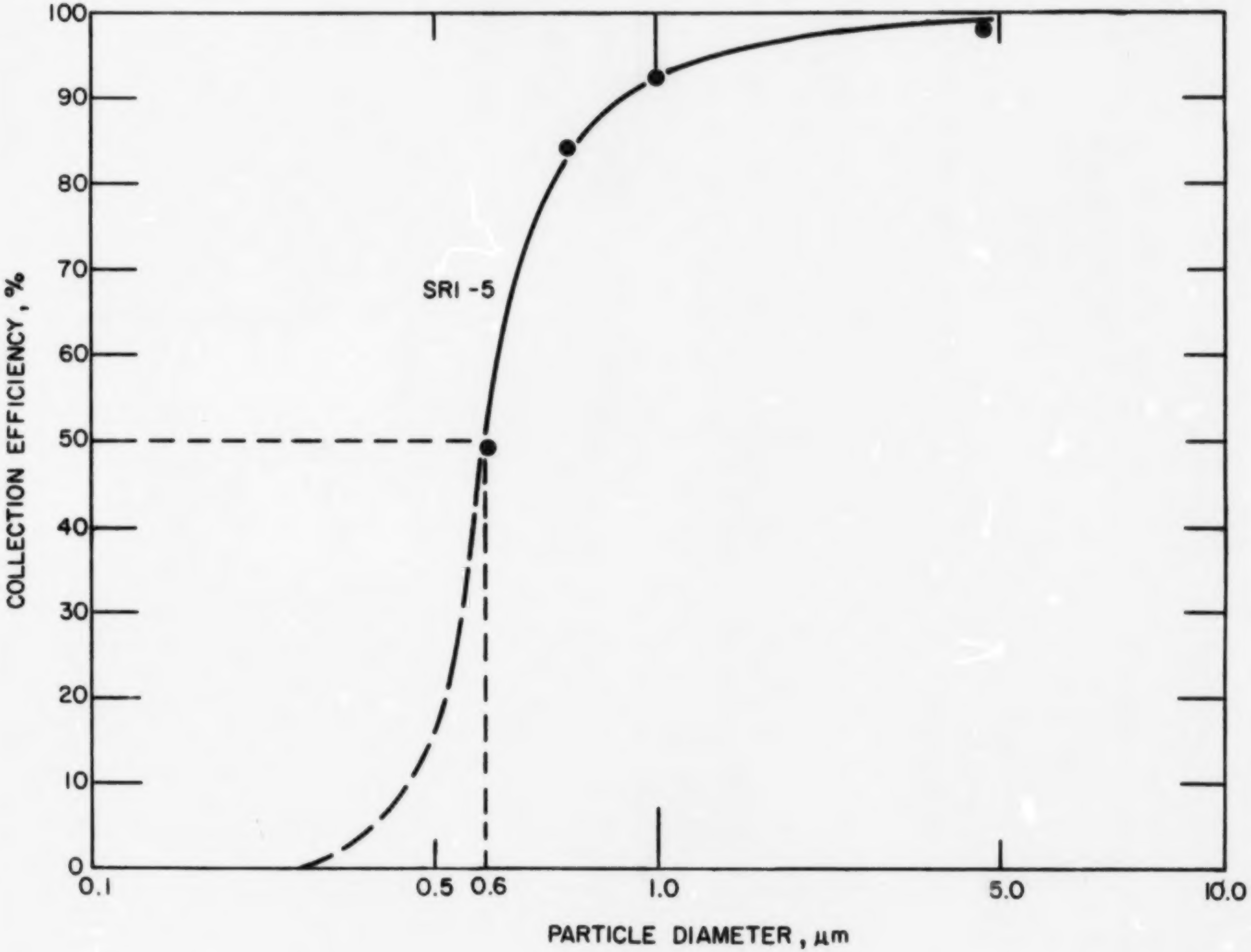
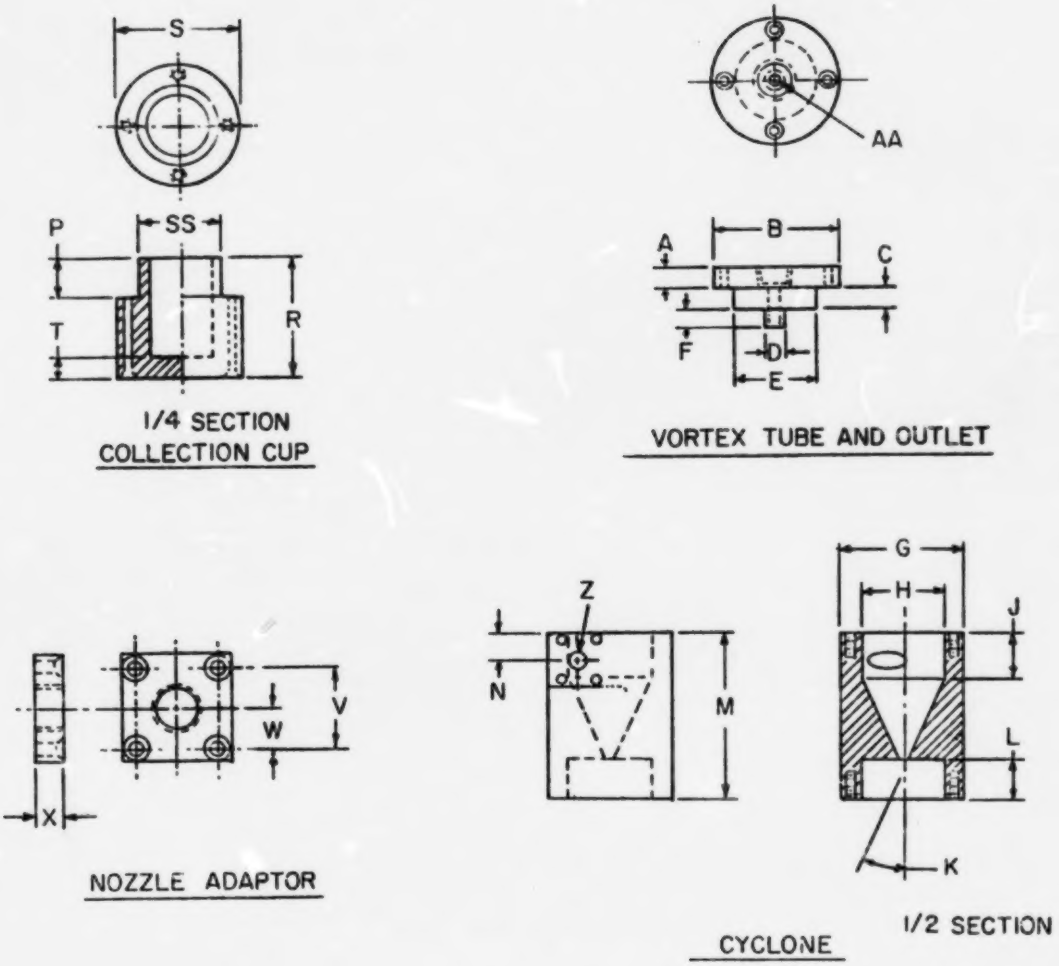


Figure C-8. Collection efficiency versus particle diameter for the SRI-5 cyclone. (22°C, 29.60 "Hg, 1.35 gm/cc, 1.0 acfm)



A	0.235	N	0.35
B	1.50	P	1.000
C	0.25	R	1.50
D	0.300	S	1.50
E	1.00	T	0.25
F	0.23	V	0.70
G	1.500	W	0.25
H	1.00	X	0.25
J	.556	Z	0.201
K	24°	AA	0.234
L	1.000	SS	1.00
M	2.063		

Figure C-9. Engineering dimensions (inches) for Cyclone SRI-5.

F. CYCLONE T1B

This design was originally developed by Chang while at McCrone Associates, and was one of the four cyclones in his parallel cyclone sampling system. Cyclones SRI-4 and SRI-5 were designed after this particular cyclone. The calibration curve for cyclone T1B is illustrated in Figure C-10 and the shop drawings are depicted in Figure C-11.

G. CYCLONE T2A

This design was also developed by Chang[3] as part of his parallel cyclone sampling system. The same internal dimensions were used in the first stage cyclone of the SRI three-stage series cyclone system. This cyclone design has been calibrated at three flowrates illustrated in Figures C-12, C-13, and C-14. Figure C-15 shows shop drawings for the SRI version of this cyclone.

H. CYCLONE T3A

This is the largest cyclone in Chang's parallel cyclone sampling system, with a nominal D_{50} of about 5 μm at 3 acfm. No calibration data are available for this cyclone. This design was used as the 3 μm D_{50} unit for the Aerotherm 5 acfm sampling system. Shop drawings are shown in Figure C-16.

I. ANDERSEN PRECOLLECTOR CYCLONE

Designed, built, and sold by Andersen 2000, Inc., for use as a precollector for the Andersen Mark III Cascade impactor, this cyclone has been calibrated by Andersen and by SRI. Calibration data and dimensions are given for this cyclone in Figures C-17, C-18, and C-19.

J. VARIATIONS IN D_{50} WITH AEROSOL SAMPLE FLOWRATE

As stated in Section IIIA, the D_{50} for a cyclone theoretically should vary as the square root of the flowrate, and the D_{50} for a range

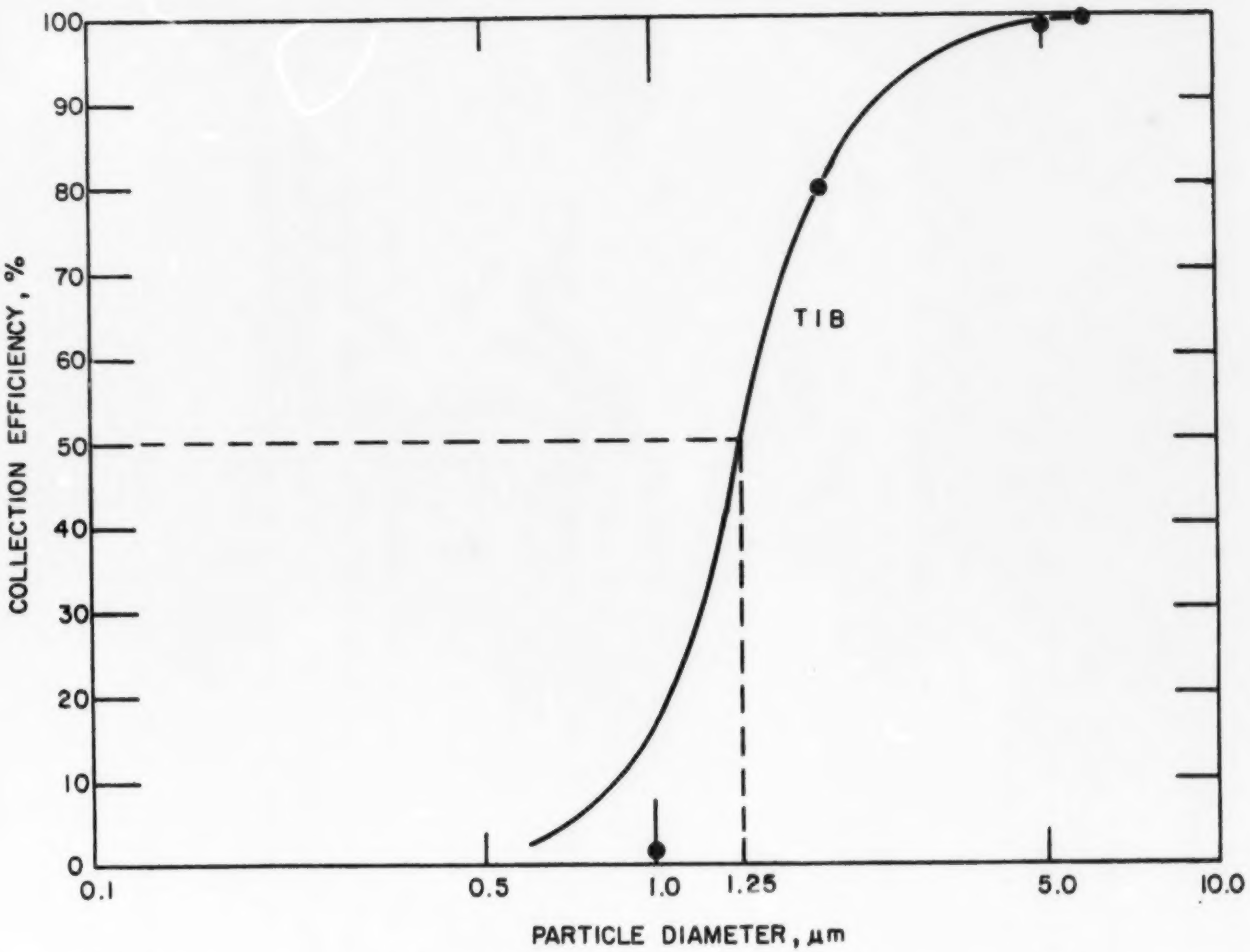
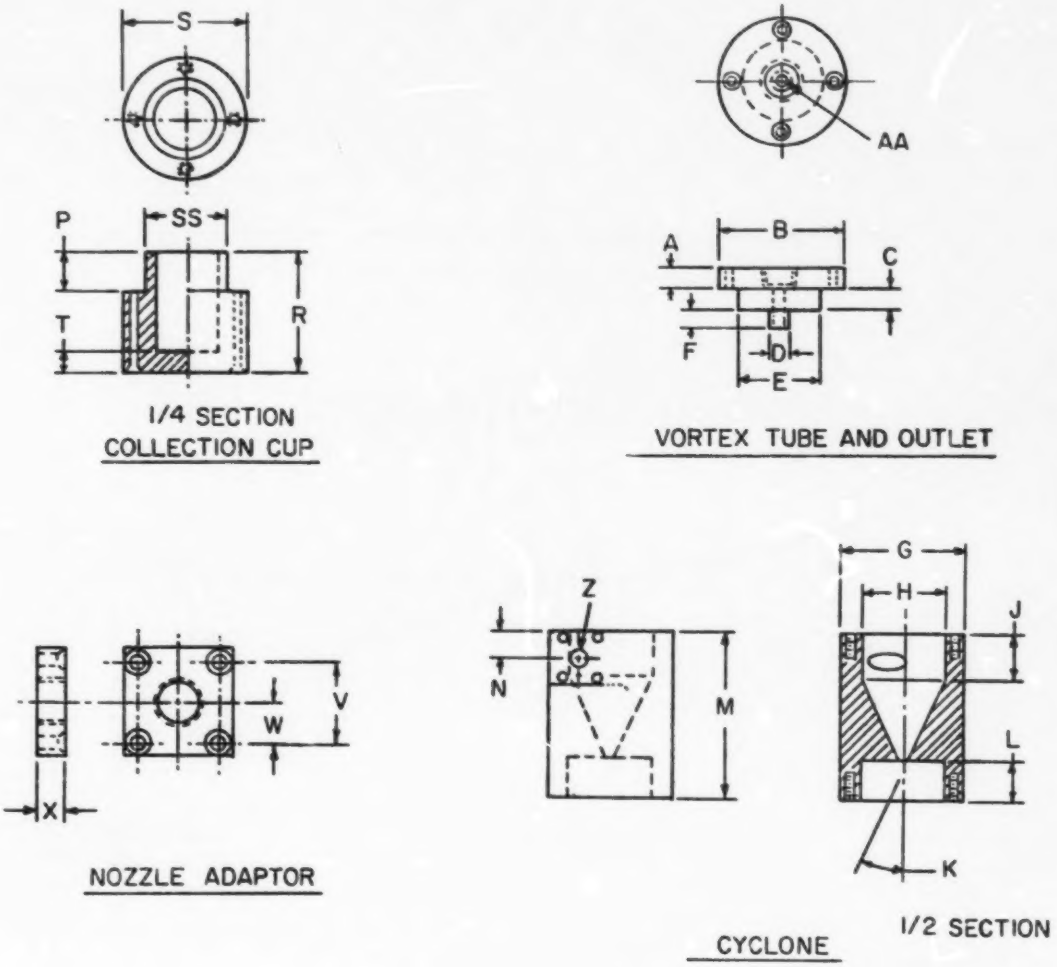
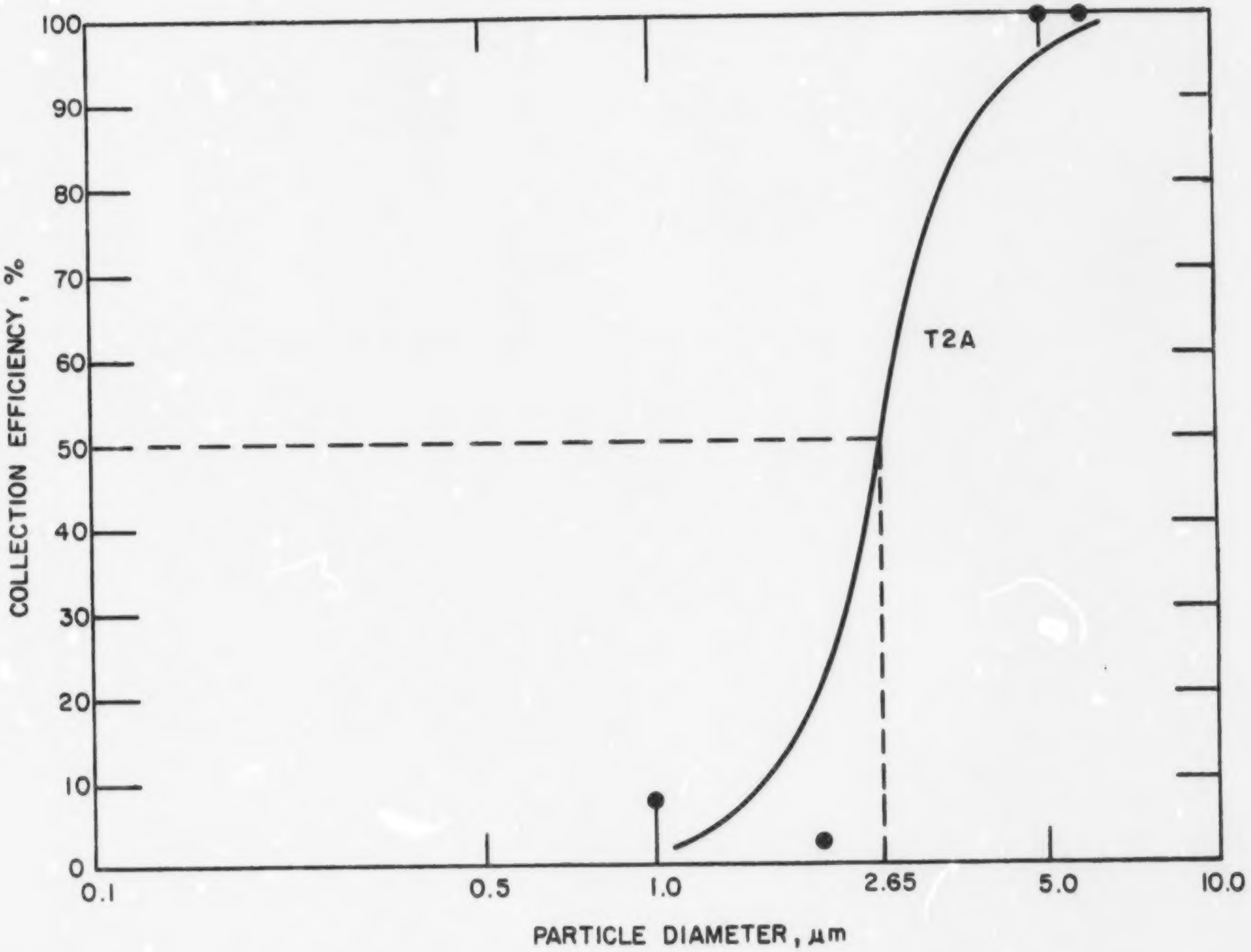


Figure C-10. Collection efficiency versus particle diameter for Cyclone T1B. (22°C, 29.60 "Hg, 1.35 gm/cc, 0.23 acfm)



A	0.235	N	0.35
B	1.50	P	1.000
C	0.25	R	1.50
D	0.300	S	1.50
E	1.00	T	0.25
F	0.23	V	0.70
G	1.500	W	0.25
H	1.00	X	0.25
J	.556	Z	0.201
K	24°	AA	.156
L	1.000	SS	1.00
M	2.063		

Figure C-11. Engineering dimensions (inches) for Cyclone T1B.



C-12. Collection efficiency versus particle diameter for Cyclone T2A. (22°C, 29.60 "Hg, 1.35 gm/cc, 1.60 acfm)

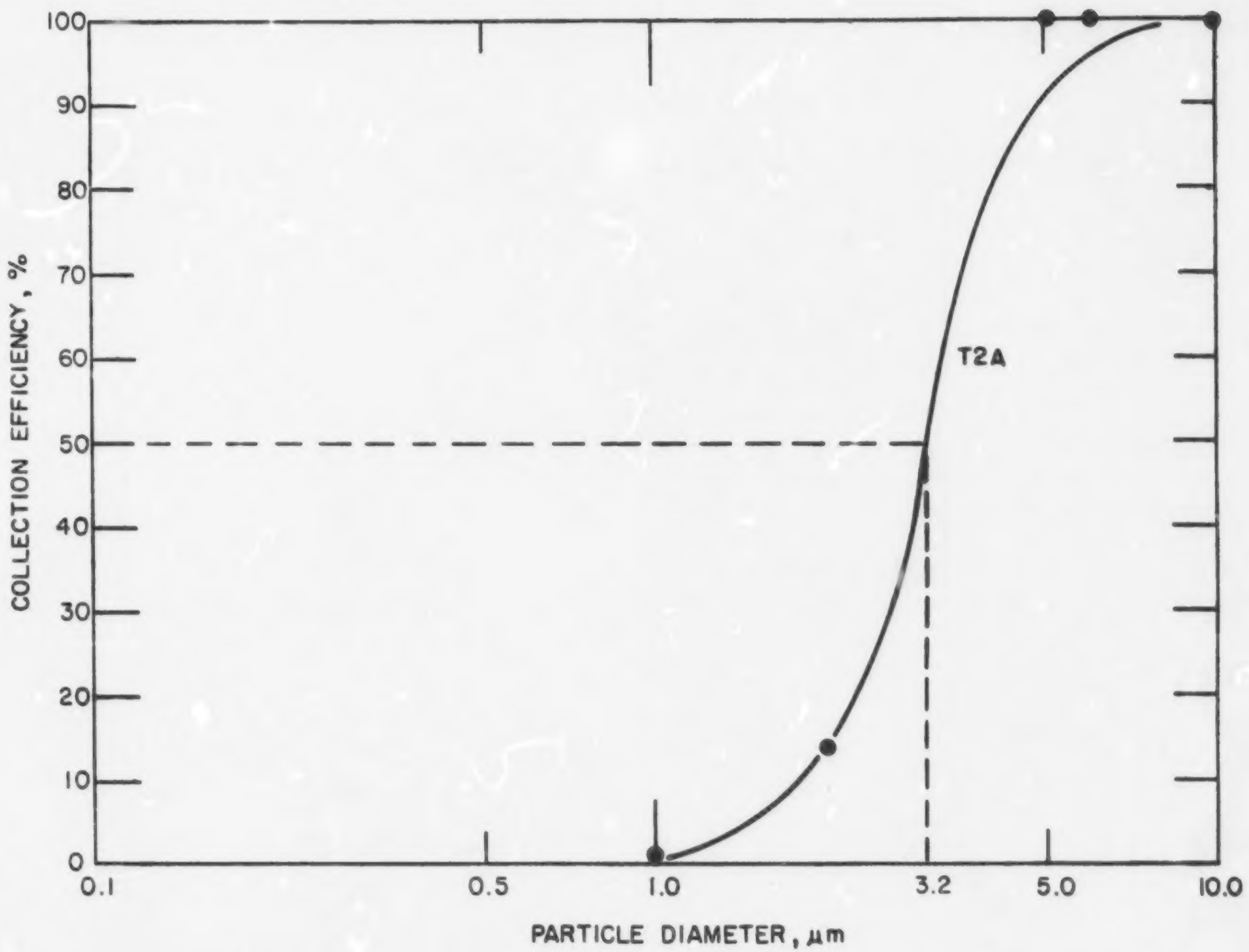


Figure C-13. Collection efficiency versus particle diameter for Cyclone T2A. ($22^{\circ}C$, 29.60 "Hg, 1.35 gm/cc, .59 acfm)

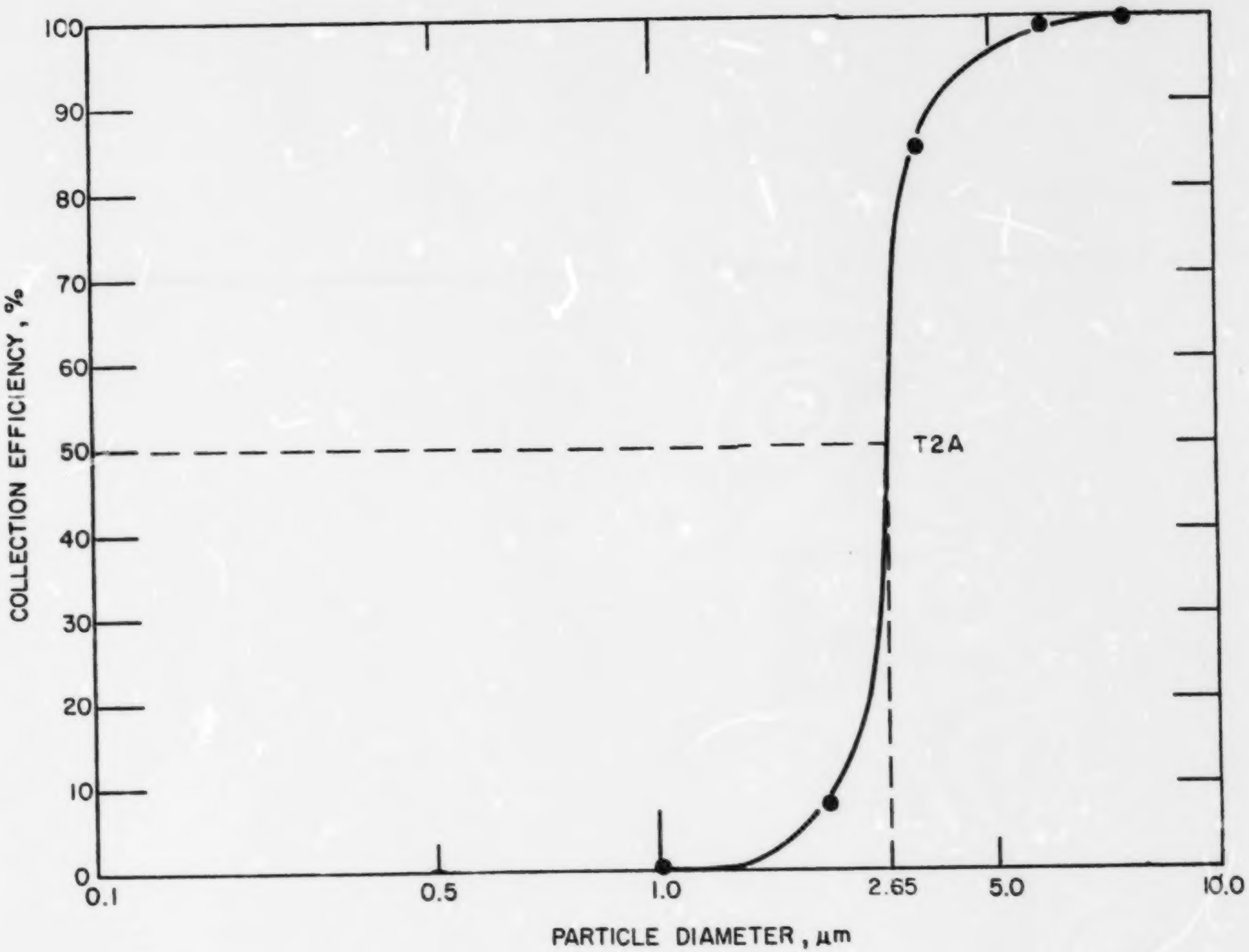
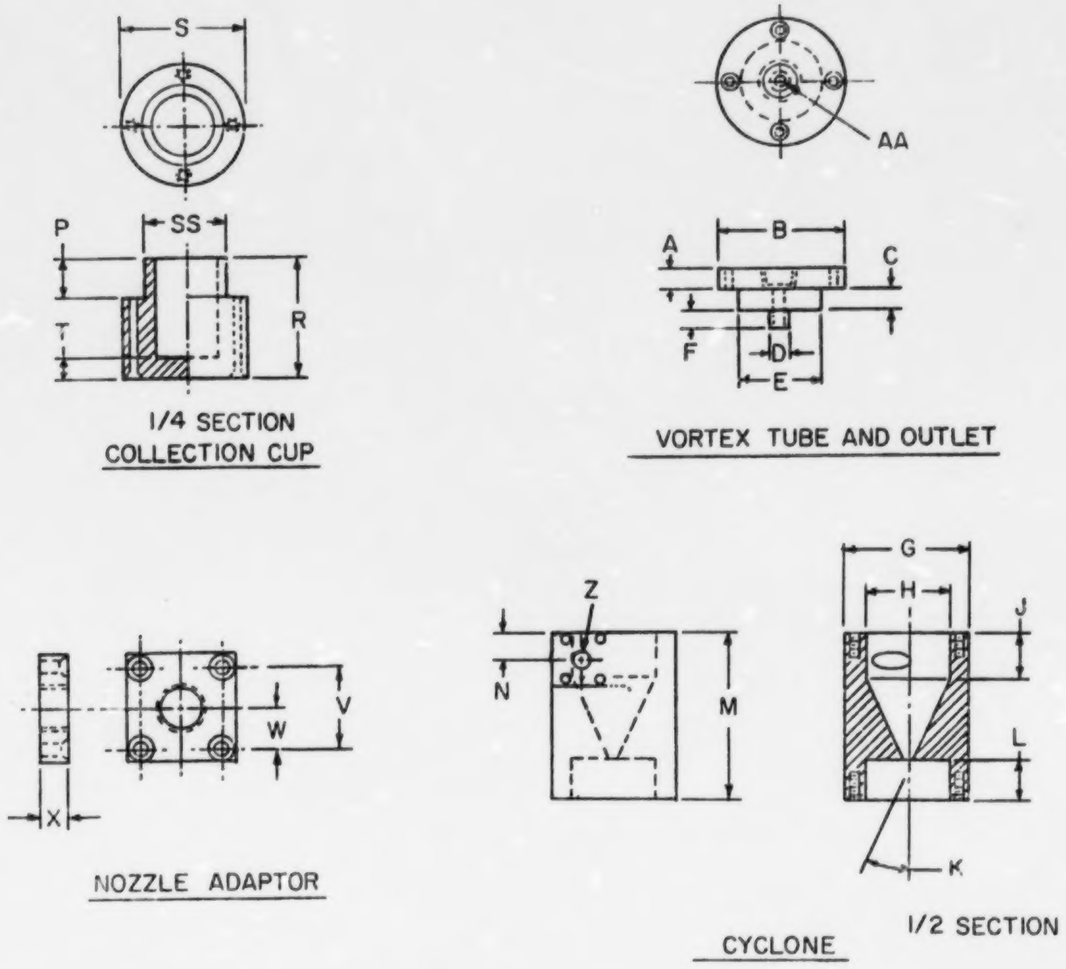


Figure C-14. Collection efficiency versus particle diameter for Cyclone T2A. (22°C, 29.60 "Hg, 1.35 gm/cc, 1.0 acfm)



A	0.5	N	0.450
B	2.0	P	0.50
C	0.25	R	1.25
D	0.465	S	2.00
E	1.430	T	0.25
F	0.618	V	0.90
G	2.000	W	0.35
H	1.440	X	0.25
J	1.080	Z	0.397
K	14°5'	AA	0.414
L	0.75	SS	1.50
M	3.685		

Figure C-15. Engineering dimensions (inches) for Cyclone T2A.

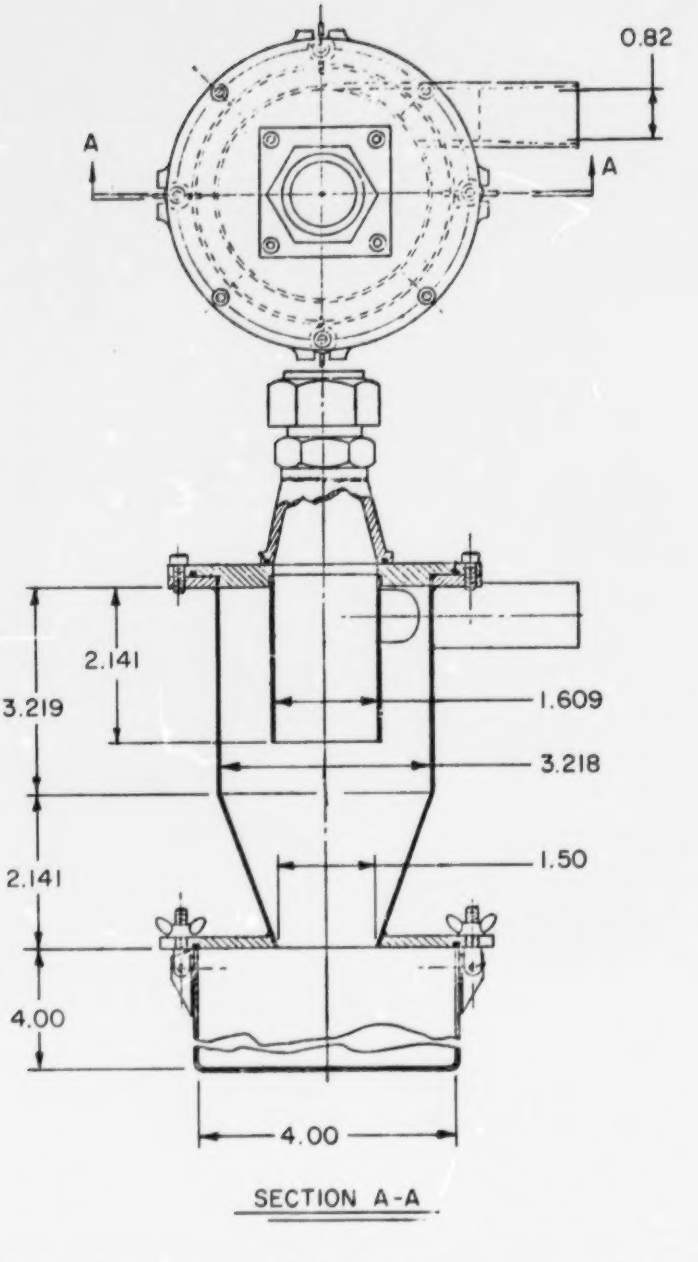


Figure C-16. Engineering dimensions (inches) for Cyclone T3A.

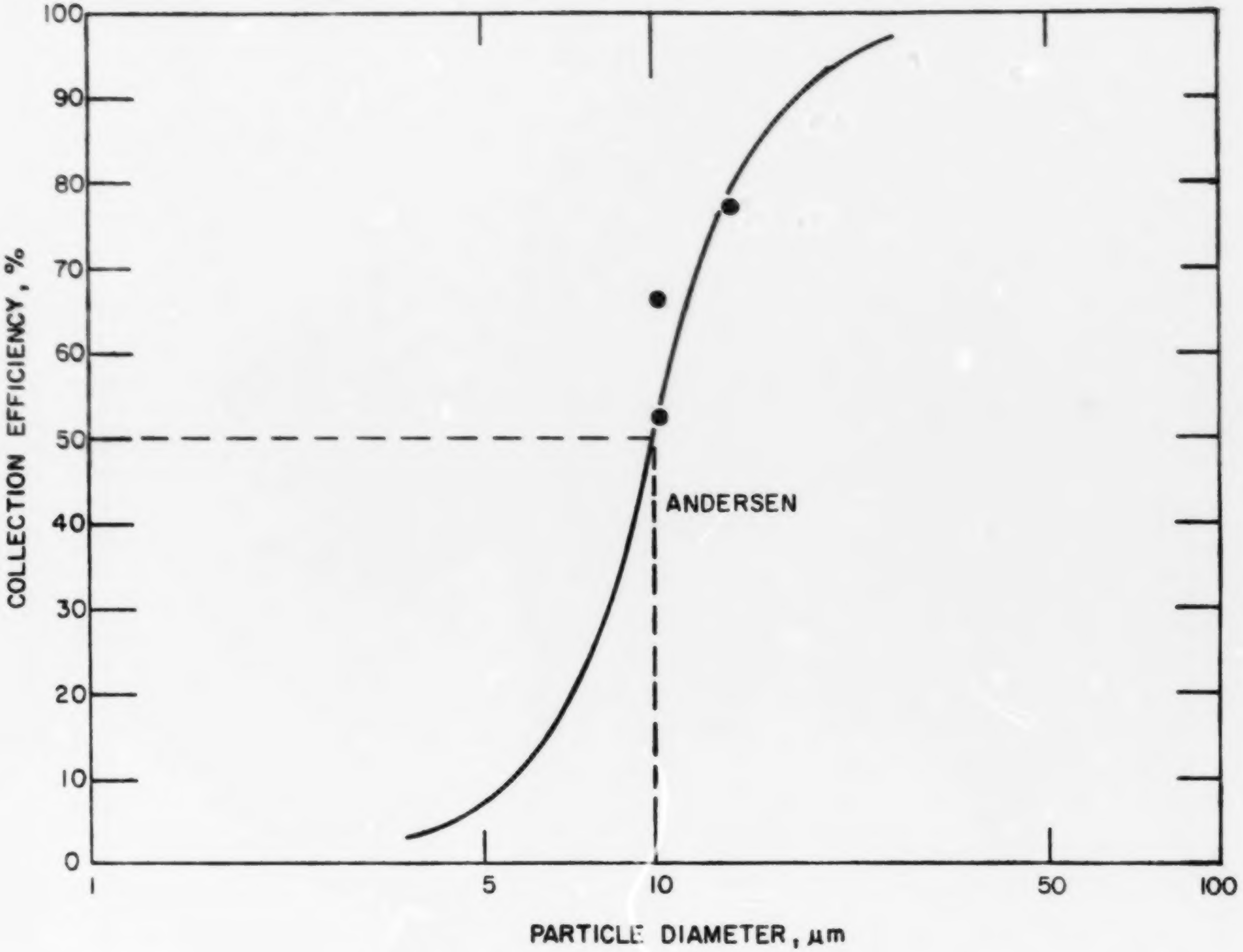


Figure C-17. Collection efficiency versus particle diameter for Andersen Modified Pre-separator. 22°C, 29.5 "Hg, 1.35 gm/cc, 0.5 acfm.

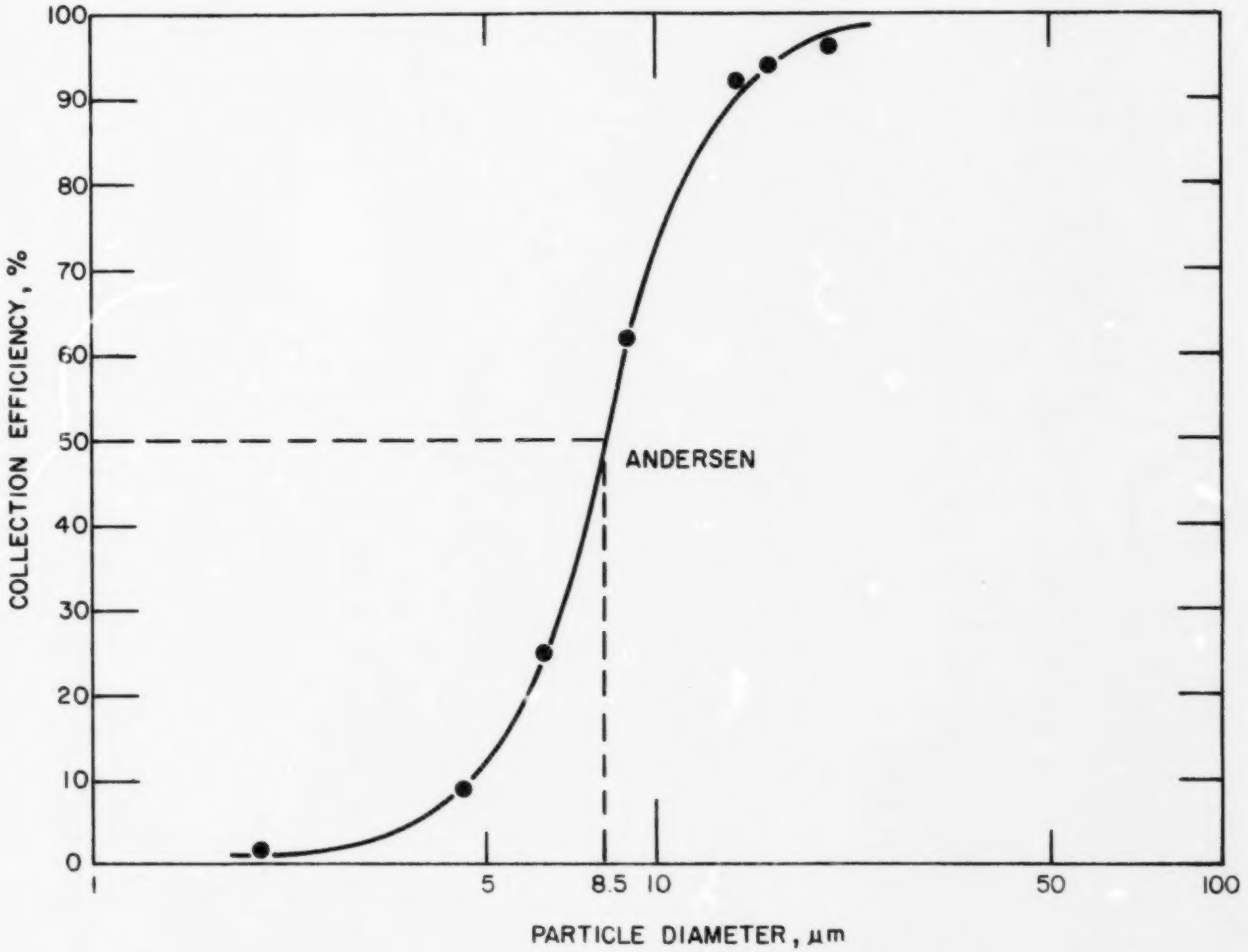


Figure C-18. Collection efficiency versus particle diameter for the Andersen Modified Pre-separator.[12] (0.75 acfm, 1.32 gm/cc, particle diameter unknown).

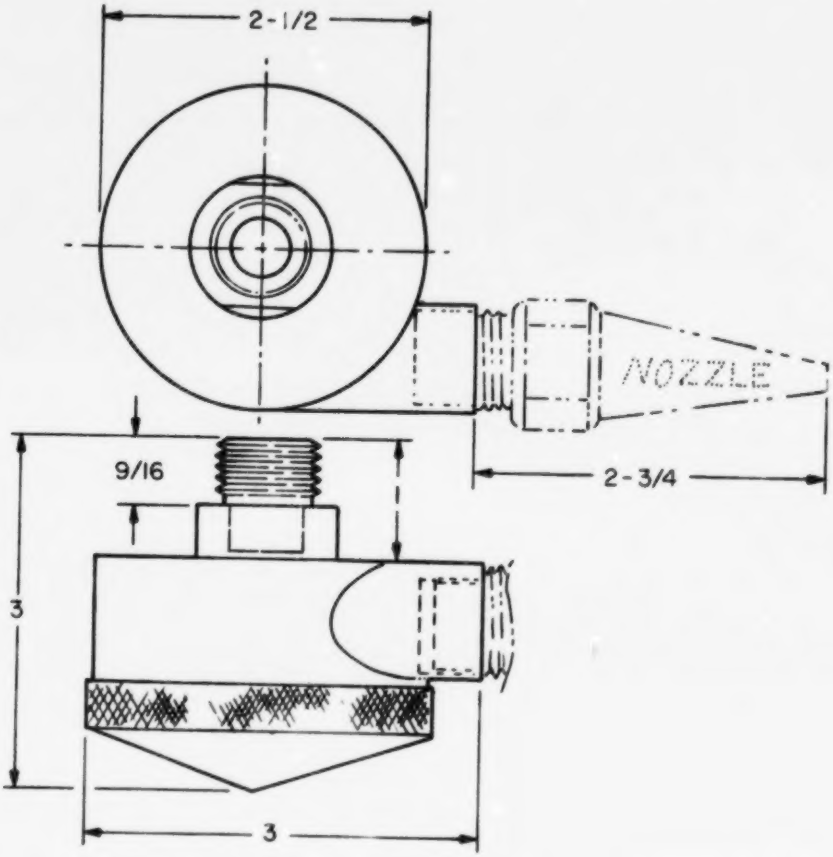


Figure C-19. Engineering dimensions (inches) for the Andersen Modified Pre-separator.[12]

of flowrates is related to the calibration D_{50} by the equation

$$D_{50}(2) = D_{50}(1)\sqrt{\frac{V_2}{V_1}} \quad ,$$

where V_1 = the calibration flowrate,

V_2 = the second flowrate of interest,

$D_{50}(1)$ = the calibration D_{50} at flowrate V_1, and

$D_{50}(2)$ = the D_{50} at the second flowrate of interest.

Figure C-20 shows the theoretical relationships between D_{50} and flowrate for each cyclone we have tested, and the experimental data which is available for each.

K. NOZZLE SPECIFICATIONS

Figure C-21 provides specifications for the construction of nozzles similar to those used with the SRI 3-stage series cyclone. These ten nozzles allow a wide range of flue gas velocities to be sampled while maintaining isokinetic sampling.

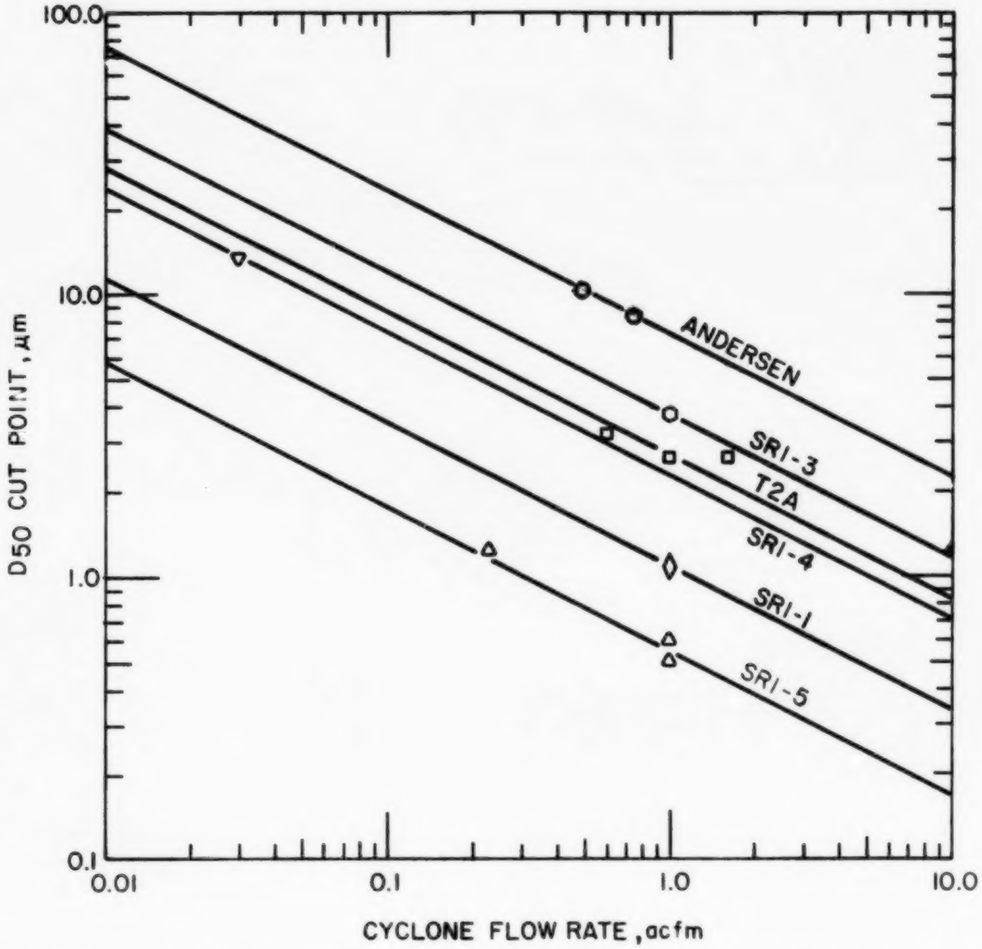
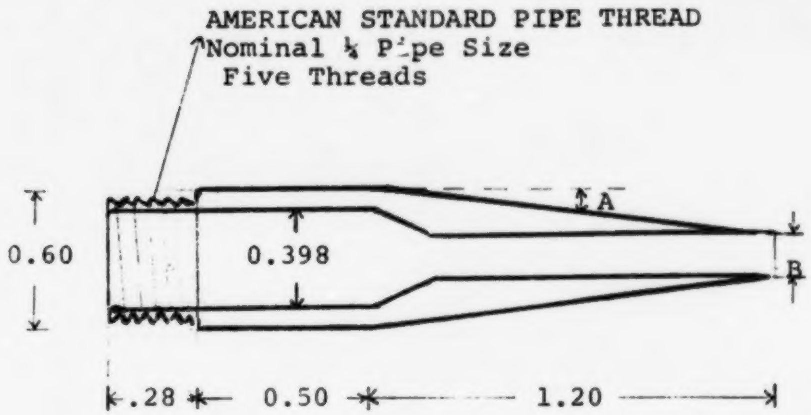


Figure C-20. D_{50} cut point versus cyclone flowrate for six calibrated cyclones.

SOUTHERN RESEARCH INSTITUTE THREE-STAGE SERIES CYCLONE

NOZZLE SPECIFICATIONS



ALL DIMENSIONS IN INCHES

Nozzle Number	A	B
1	9° 46'	0.177
2	9° 19'	0.196
3	8° 55'	0.213
4	8° 21'	0.238
5	7° 25'	0.277
6	6° 30'	0.316
7	5° 29'	0.358
8	4° 36'	0.397
9	3° 41'	0.435
10	2° 45'	0.475

Figure C-21. Cyclone nozzle design specifications.

APPENDIX D

CONVERSION TABLE FOR UNITS

To Convert From	To	Multiply By
°F	°C	(°F-32) 5/9
ACFM or acfm	m^3/sec	0.000472
"H_2O	mm Hg	1.8682
inches	mm	25.4
ft^3	m^3	0.02832

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